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OBSERVING TIDAL DISRUPTION EVENTS WITH RUBIN OBSERVATORY LSST

Growing Black Holes: Accretion and Mergers

Kathmandu, May 17th, 2022

OUTLINE

- very brief history of TDEs
- TDEs theoretical picture & observations
- prospects in the era of Rubin Legacy Survey of Space and Time (LSST)

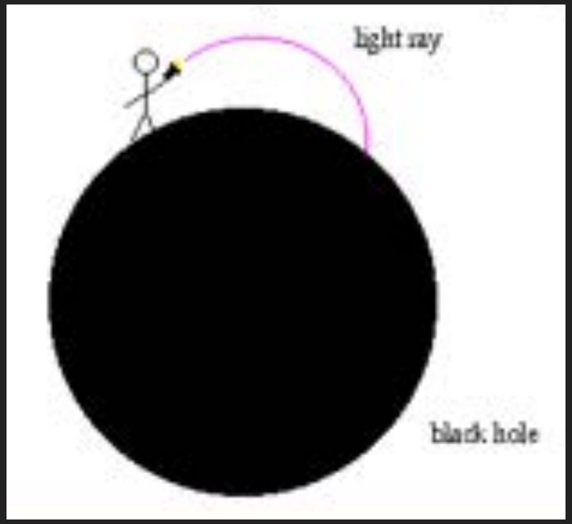
SHORT HISTORY OF AN IDEA

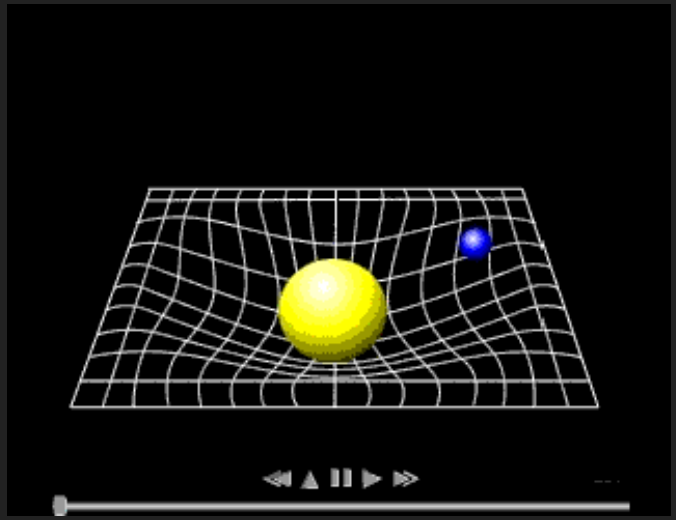
- BH idea - “dark stars” - John Michell, Pierre Simon de Laplace (1783, 1795)
- general theory of relativity - Albert Einstein (1915)
- solution of Einstein’s equations - Karl Schwarzschild (1916)

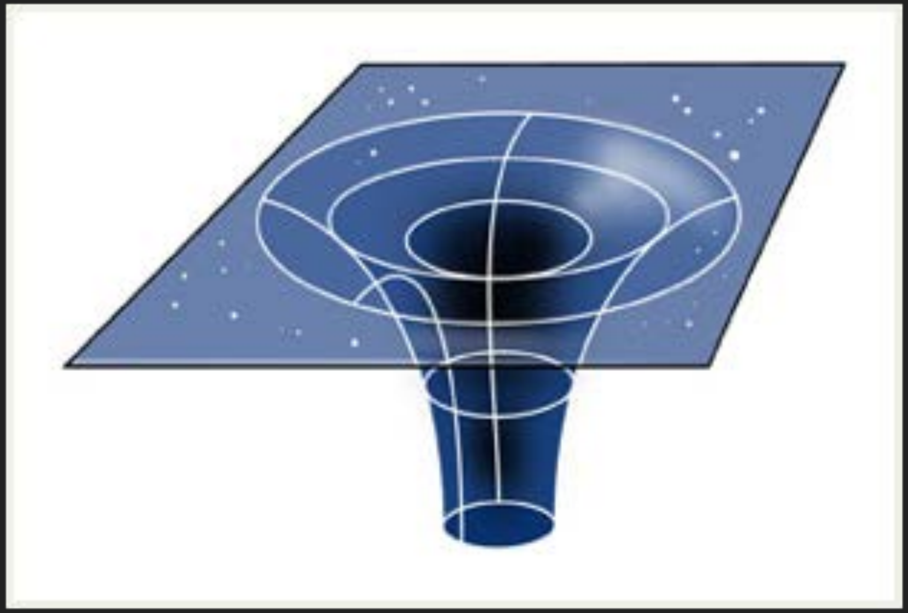
Schwarzschild radius

$$\boxed{r_{\rm Sch} = \frac{2GM_{\rm BH}}{c^2}}$$

1 $M_{\rm Earth}$	9 mm
1 M_S	3 km
10^6 M_S	4 $R_{\rm Sun}$, 0.02 a.u.
10^9 M_S	20 a.u. = $d_{\rm Sun\text{-}Uranus}$

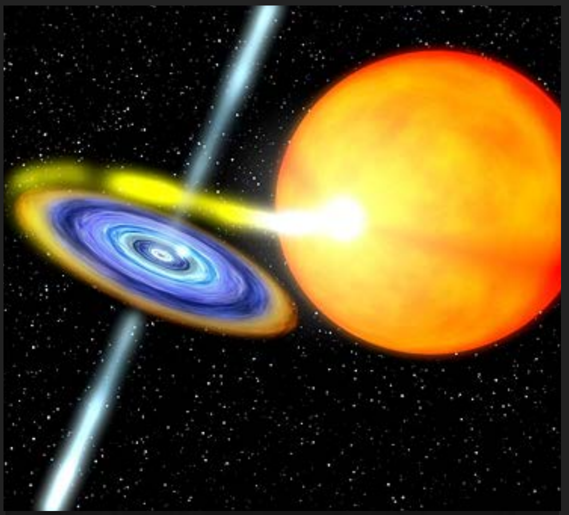






DO BHS REALLY EXIST?

- 1939 - Oppenheimer & Snyder - collapse of massive stars: *“close themselves off from any communication with a distant observer”*



- 1963 - Maarten Schmidt - distance to quasar 3C 273

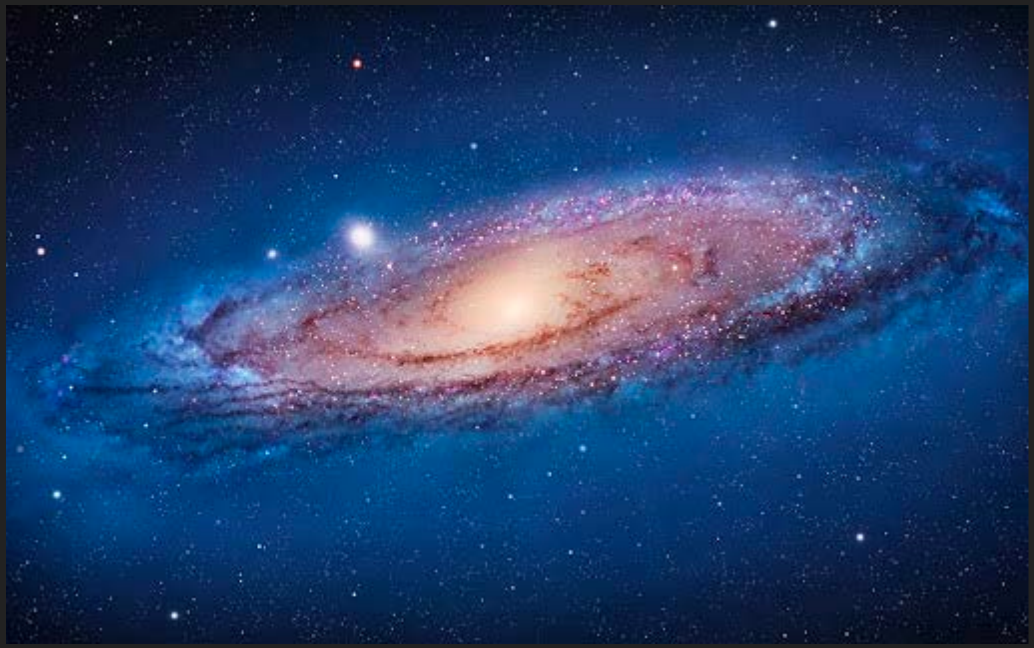
- model with a massive black hole (Salpeter 1964, Zeldovich&Novikov 1965, Lynden-Bell 1969)

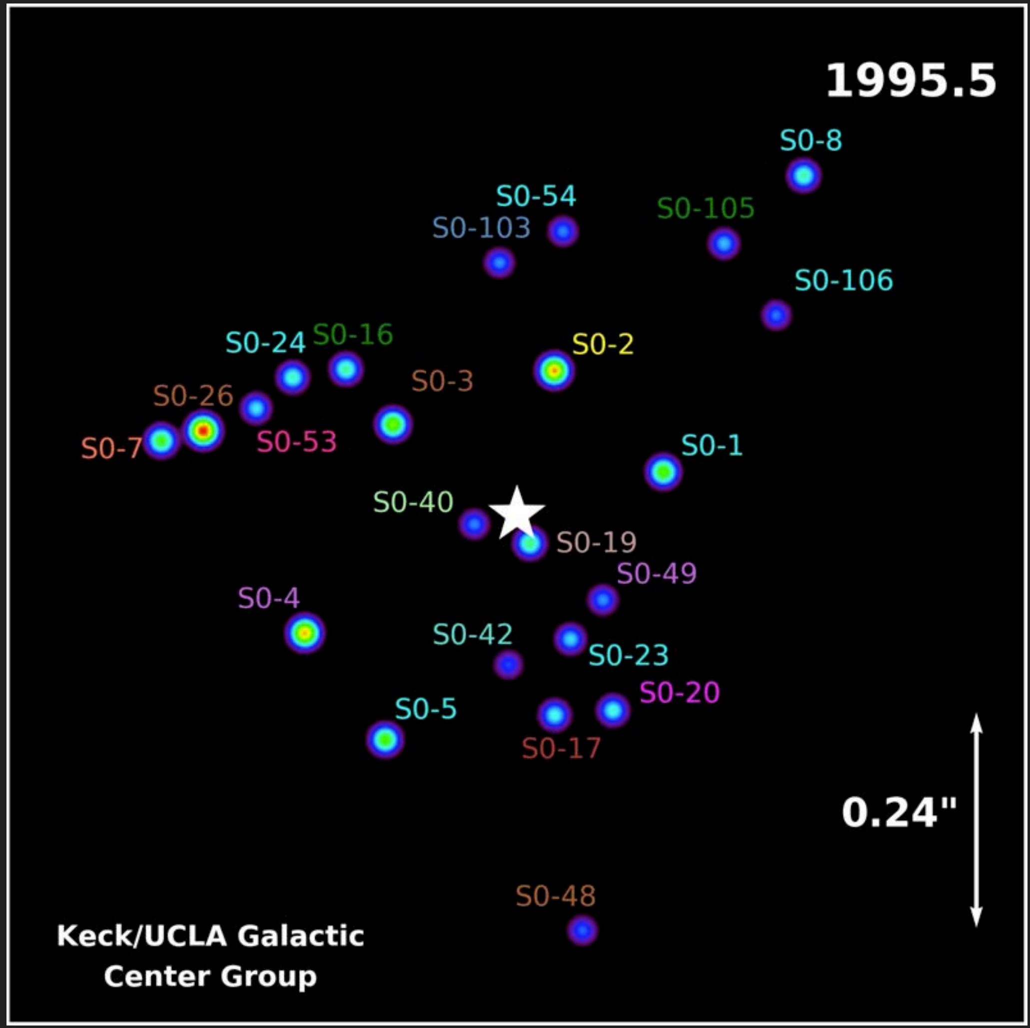
TIDAL BREAK-UP OF STARS

- Hills 1975, 1978:"tidal breakup of stars…may explain… QSOs and the nuclei of Seyfert galaxies."
- Frank&Rees 1976, Frank 1978
- Young, Shields, Wheeler 1977: **rate too low**
- Rees 1988 - TDE flares: detection of non-active MBH, evidence of a BH in Galactic centre (lack of - rule out BHs?)

NON-ACTIVE GALACTIC CENTERS

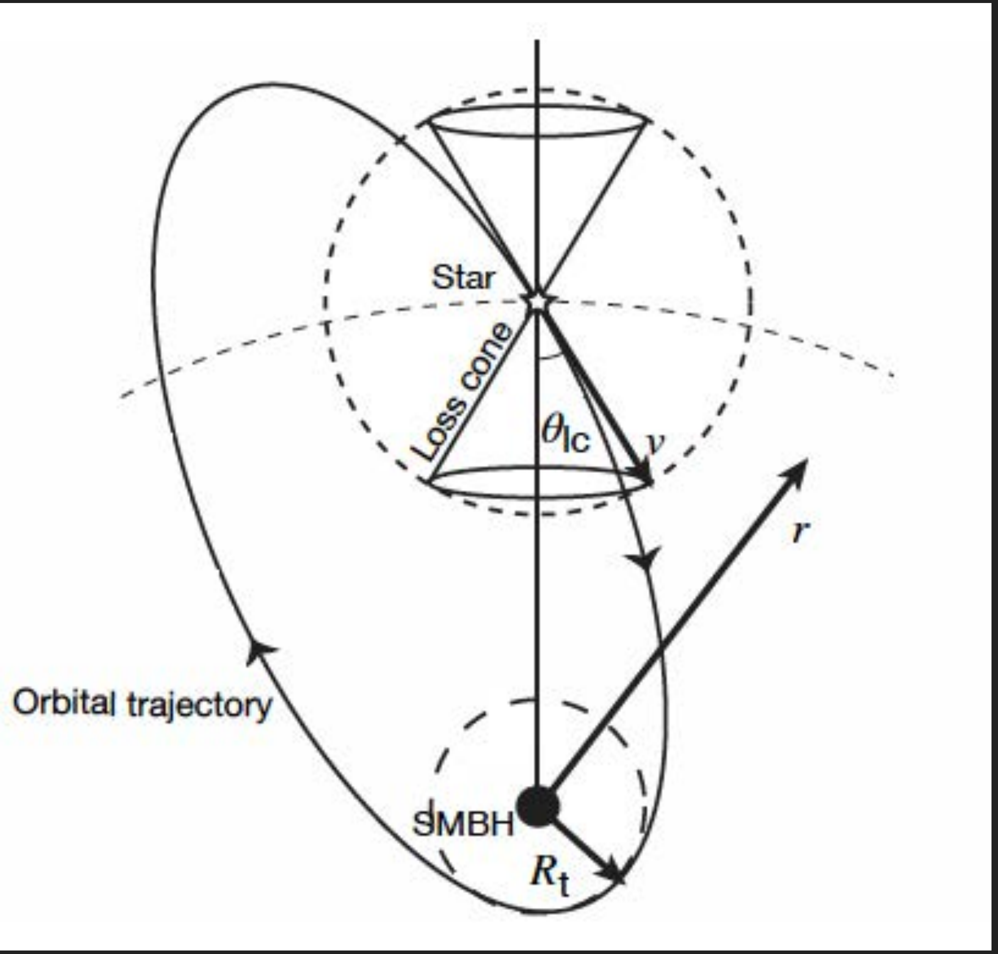
- dormant BHs in centers of (almost all?) large galaxies - dynamic of stars and gas
- supermassive black hole in the centre of our Galaxy
- gc not so well resolved in other galaxies - TDEs as probes





UNFORTUNATE STARS

- orbits shaped by: BH gravitational potential, stellar population, dynamical scattering due to interactions with other stellar mass objects
- lose cone
- repopulation
- different effects:
  - two-body relaxation
  - resonant relaxation
  - non-spherical galactic nuclei (axisymmetric, triaxial)
  - nuclear stellar disc
  - nuclear bars
  - binary MBHs
  - stellar binary TDEs
  - …



Bučar Bricman 2021, Merritt 2013

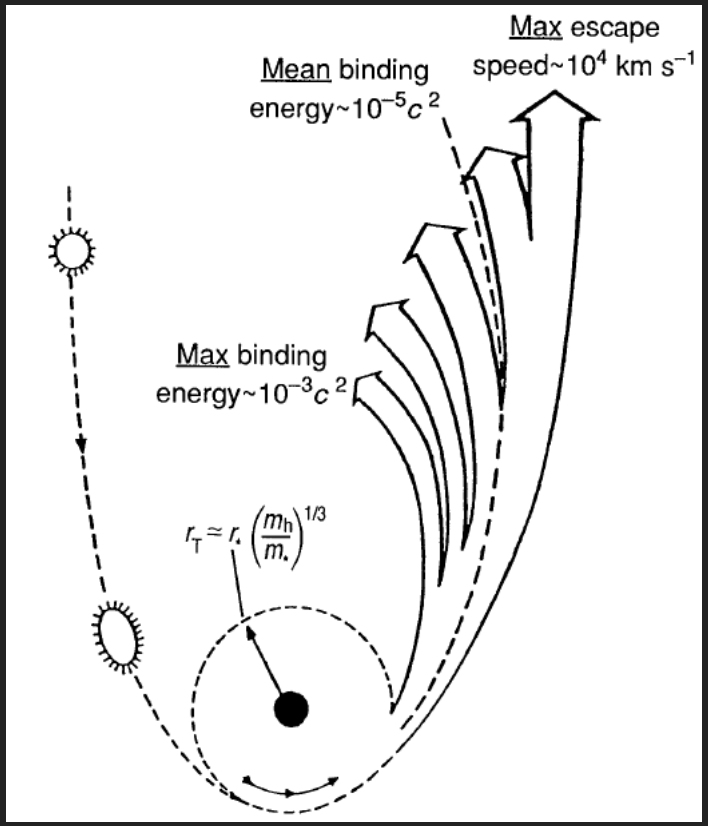
BASIC PICTURE

- tidal radius: $r_t = R_* \left(\frac{M_{BH}}{M_*}\right)^{1/3}$
- "strength" of encounter - impact parameter

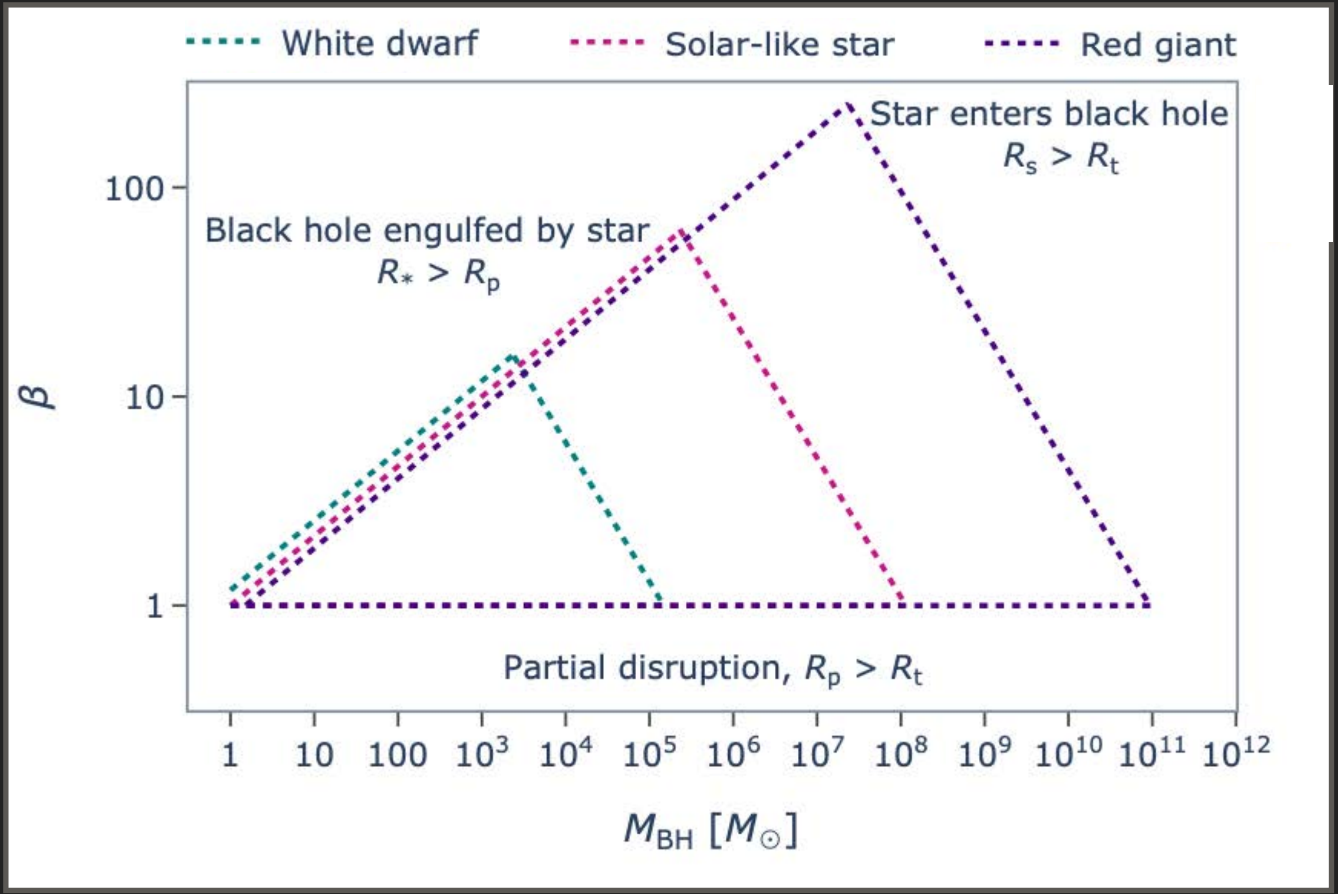
$$\beta = \frac{r_t}{r_p}$$

- $r_p <= r_t$
- $r_p > R_*$
- $r_t > r_{Sch}$

$$r_{Sch} = \frac{2GM_{BH}}{c^2}$$



Rees, 1990



from Bučar Bricman 2021

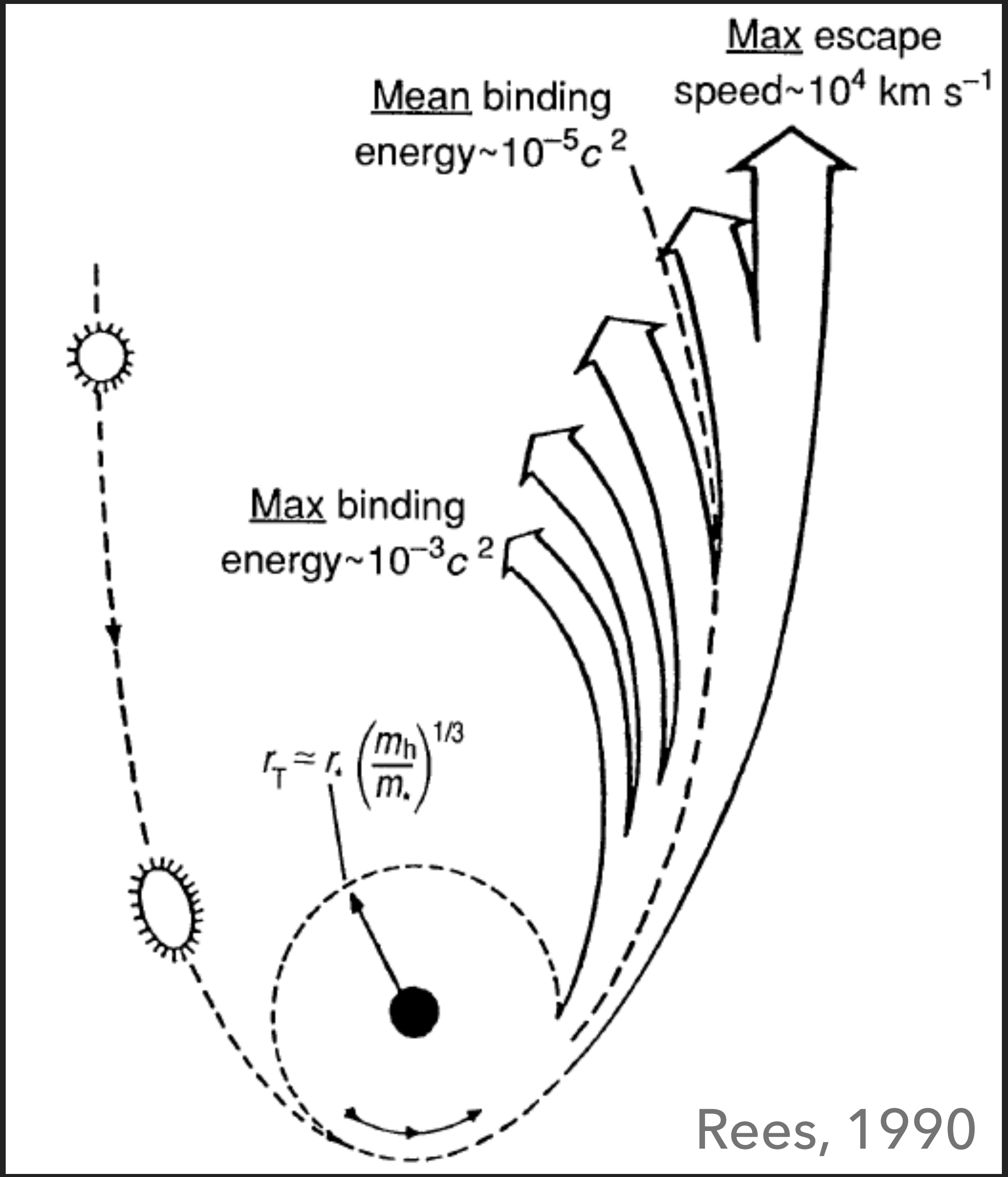
FALLBACK RATE

- Rees 1988
- parabolic orbit, non-rotating BH
- 3rd Kepler's law $\epsilon = -\frac{1}{2}\left(\frac{2\pi G M_{\rm BH}}{t}\right)^{2/3}$
- flat E distribution
- fallback rate:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \boxed{\frac{\mathrm{d}m}{\mathrm{d}\epsilon}}\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = \frac{1}{3}(2\pi G M_{\rm BH})^{2/3}\frac{\mathrm{d}m}{\mathrm{d}\epsilon}t^{-5/3}$$

- luminosity follows the fallback rate:

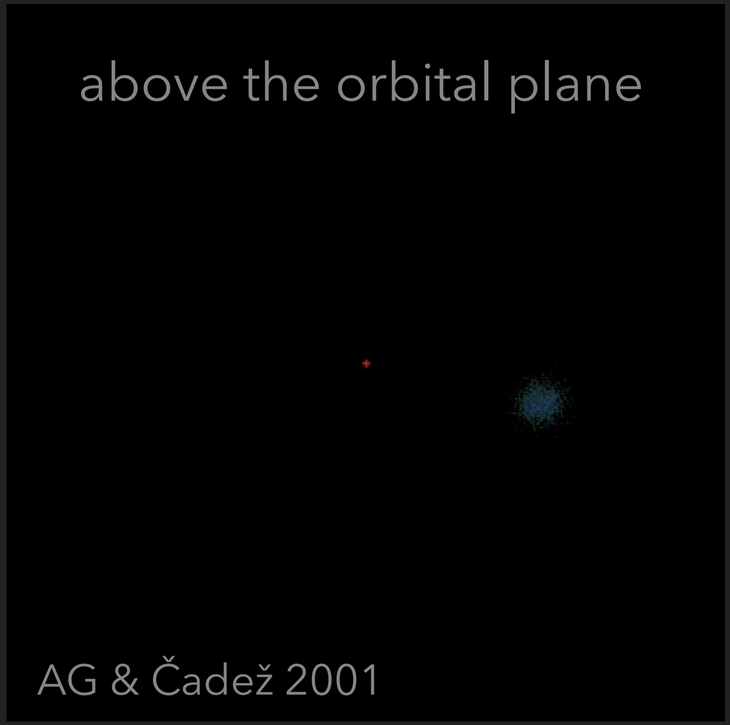
$$L \propto \dot{M}_{\rm fallback} \propto t^{-5/3}$$

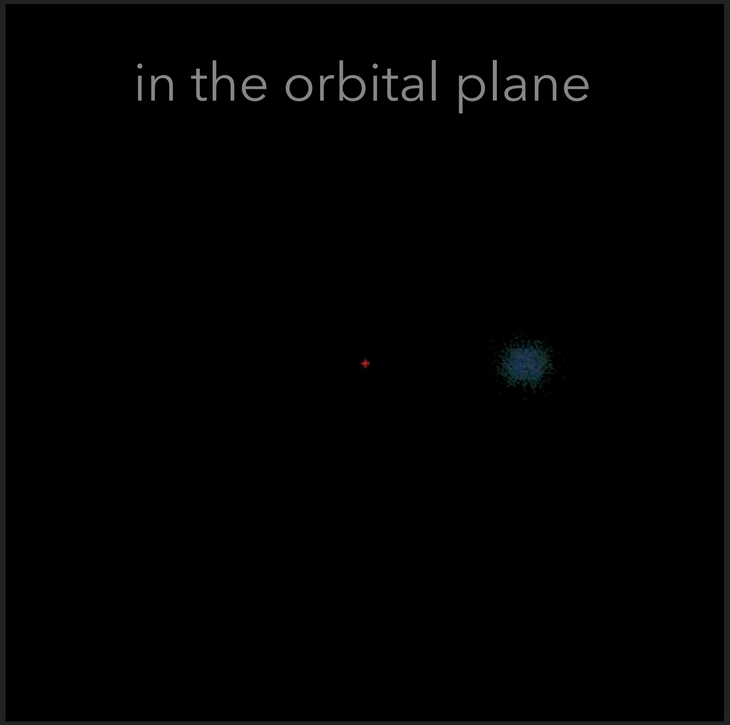


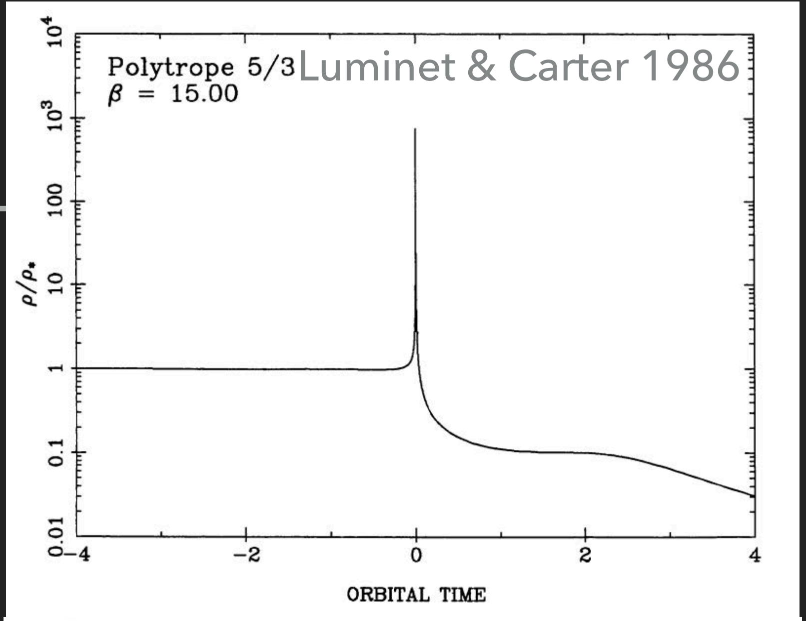
Rees, 1990

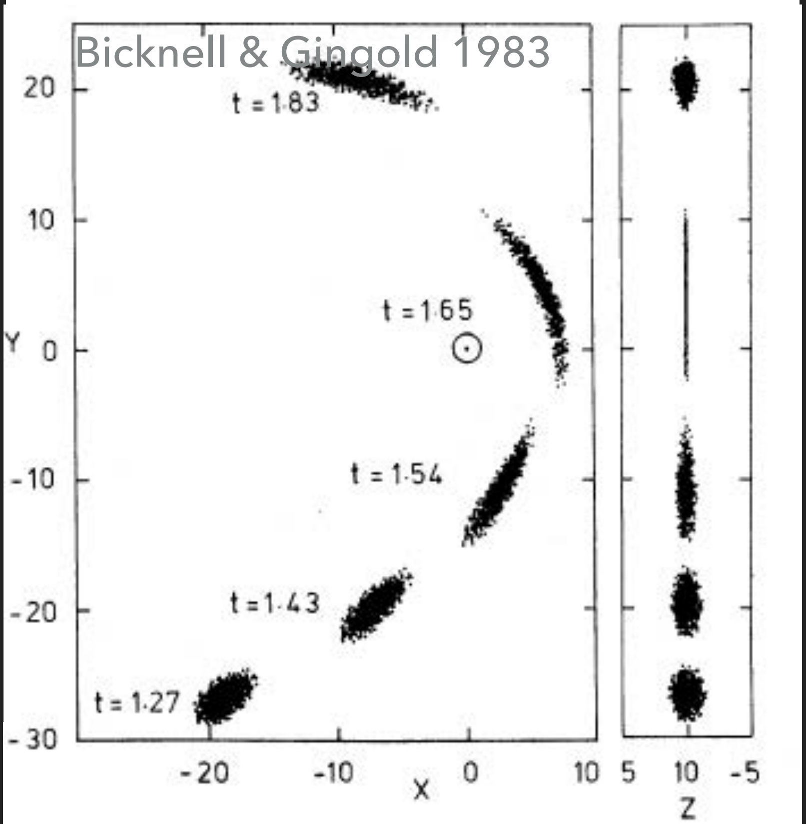
EARLY STUDIES

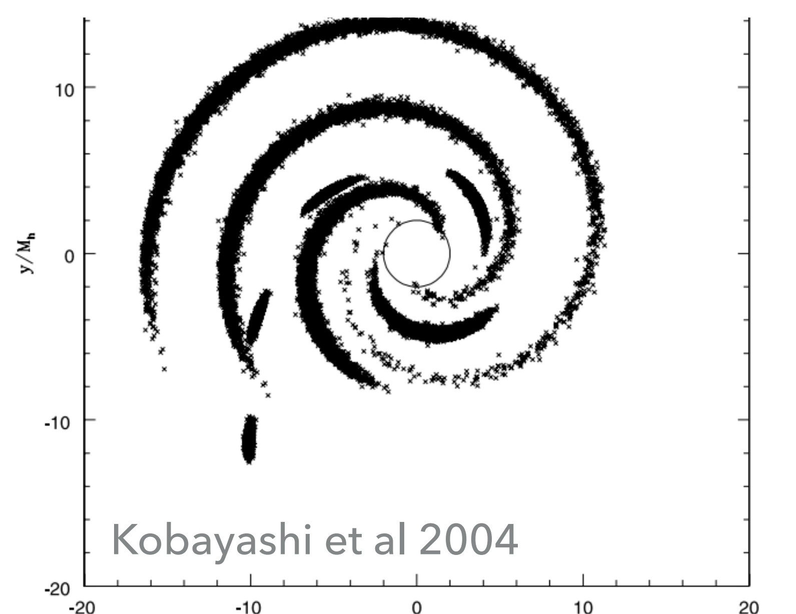
- analytical: Lidskii, Ozernoi, Carter, Luminet, Pichon, Marck, Phinney, Rees… (1979, 1982, 1985, 1989, 1989, 1988…)
- close encounters - “pancake” effect
- hydrodynamic simulations: Nolthenius & Katz 1982, Bicknell & Gingold 1983, Evans & Kochanek 1989, Laguna 1993, Khokhlov 1993, Ayal 2000…











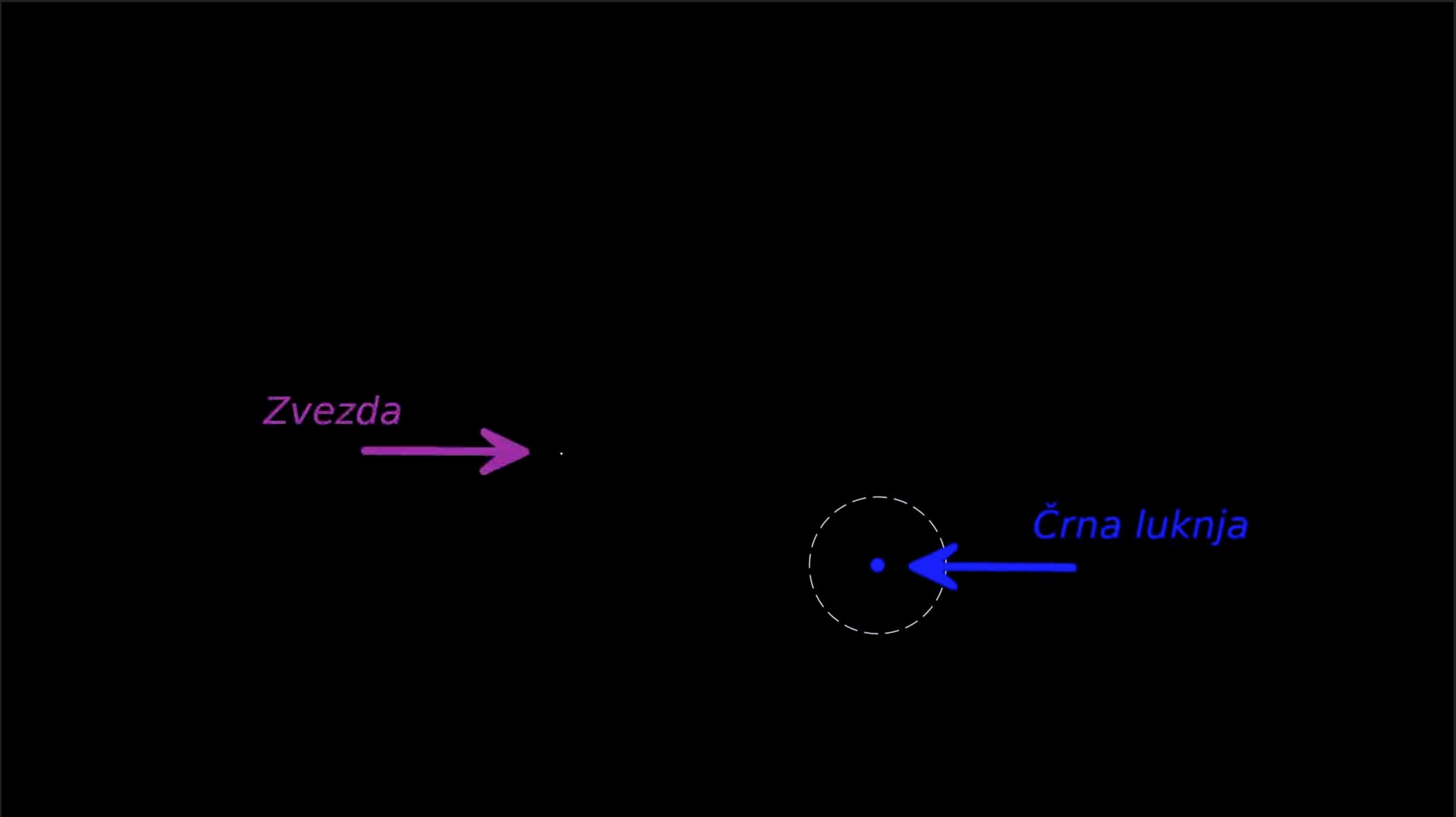
TDE MODELLING TODAY

for full GR simulations:
next talk by Taeho Ryu

- several groups: Rosswog, Lodato, Rossi, Ramirez-Ruiz, Piran, Bonnerot….
- grid-based and particle-based hydro simulations - good agreement
- “simple” - polytropic stars in Newtonian gravity - varying BH and star’s mass, beta, eccentricity (full and partial disruptions)
- more advanced: realistic - MESA star (age), GR, spin of the BH…

PHANTOM, Solar type star, e=1, beta=7

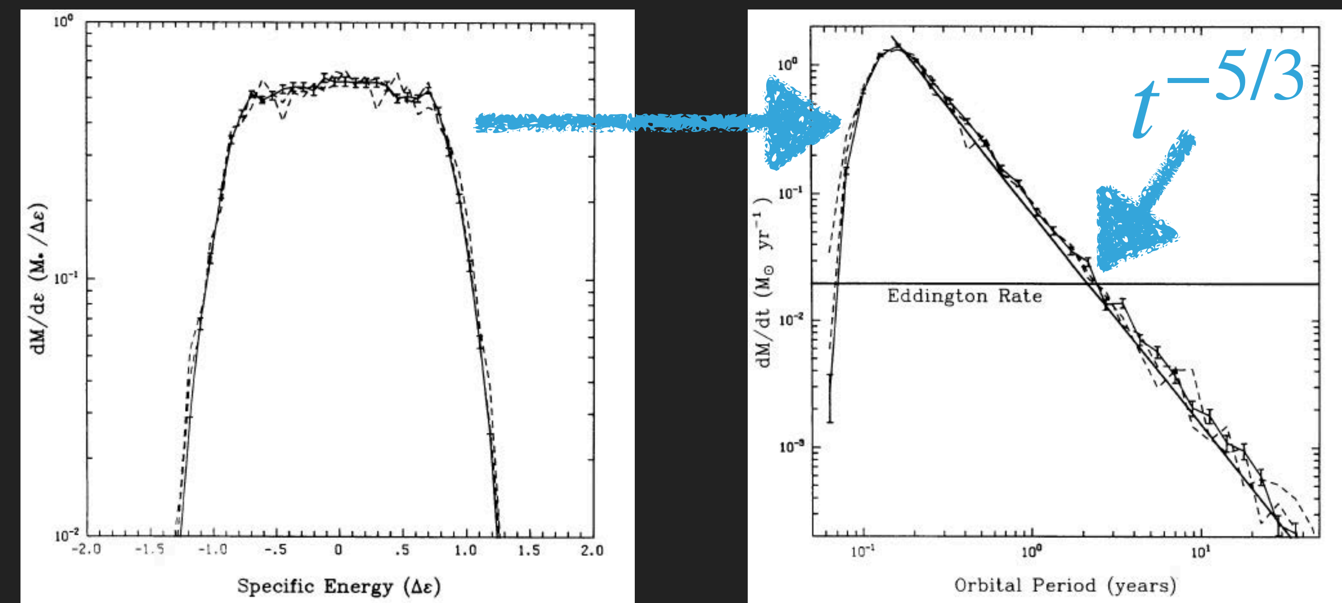
Taj Jankovič



MASS FALLBACK RATE

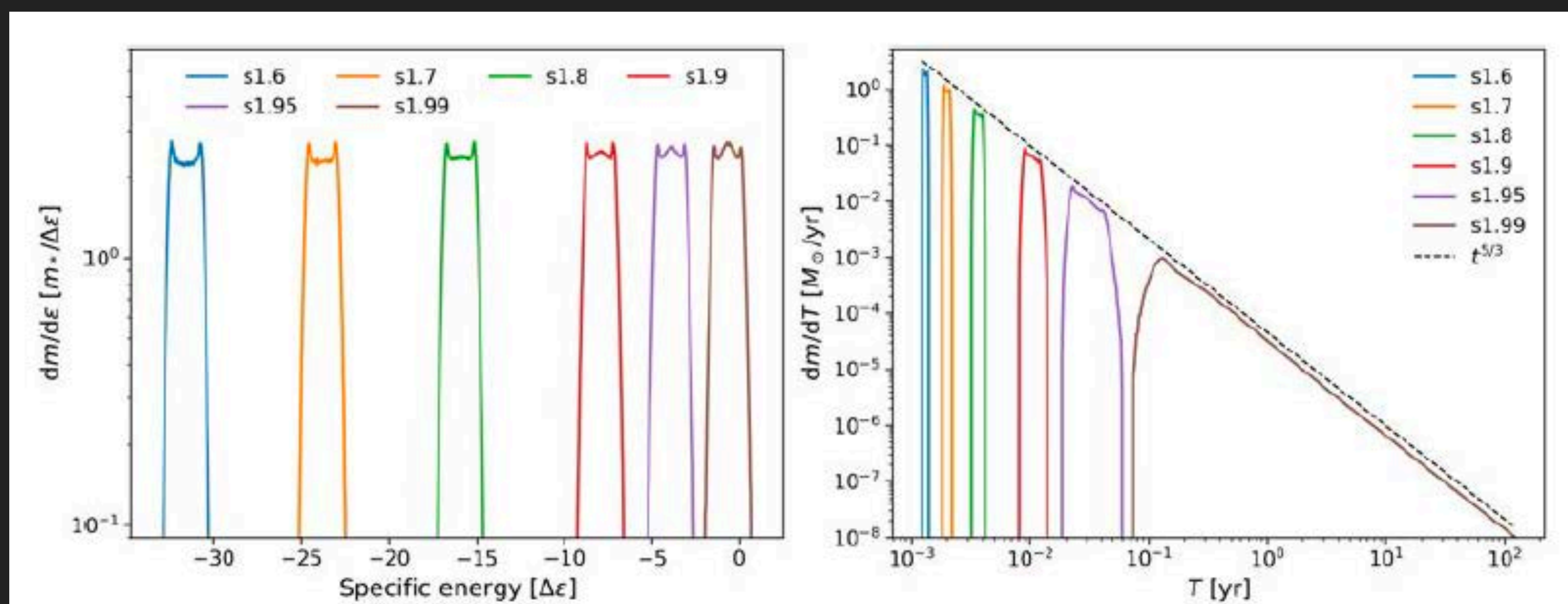
- mass fallback rate set by dM/dE (frozen in approximation)

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \boxed{\frac{\mathrm{d}m}{\mathrm{d}\epsilon}}\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = \frac{1}{3}(2\pi G M_{\mathrm{BH}})^{2/3}\frac{\mathrm{d}m}{\mathrm{d}\epsilon}t^{-5/3}$$



Evans & Kochanek 1989

PHANTOM, generalized post-Newtonian potential, polytrope 5/3, Solar type star, beta=1, varying e



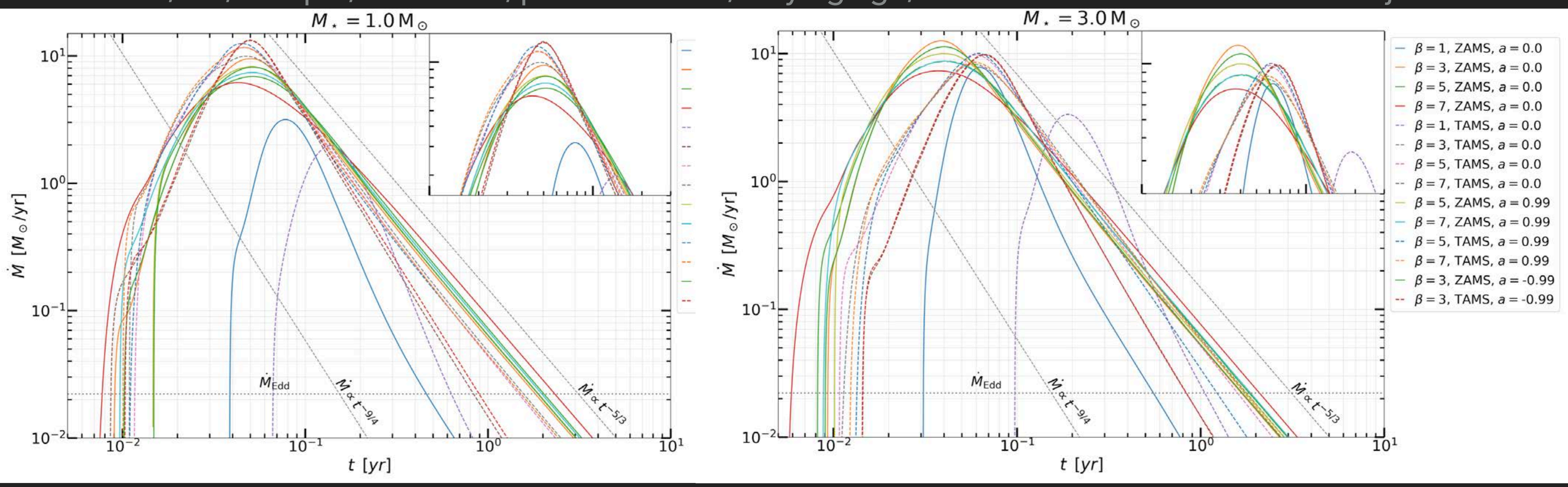
Clerici 2020

- late-time fallback rate $t^{-5/3}$ for full disruptions, but not partial

FALL BACK RATE

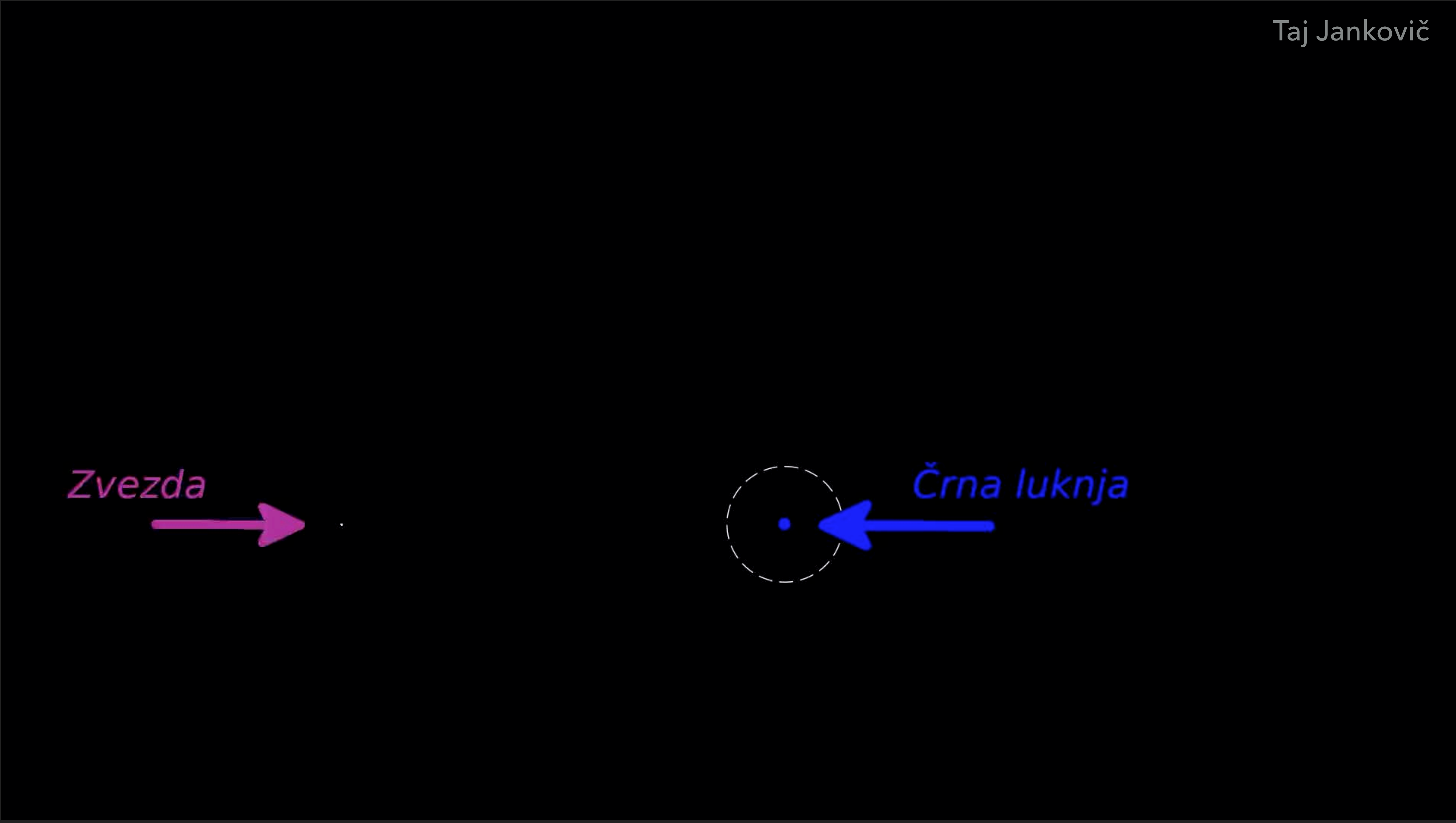
- stellar type, age - MESA (Paxton et al. 2011)
- Law-Smith et al. 2019, 2020…
- preliminary by Taj:

PHANTOM, GR, BH spin, MESA star, parabolic orbit, varying age, beta   Taj Jankovič



SELF-CROSSING AND DEBRIS CIRCULARIZATION

PHANTOM, Solar type star, e=0.95, beta=5



IDEALLY

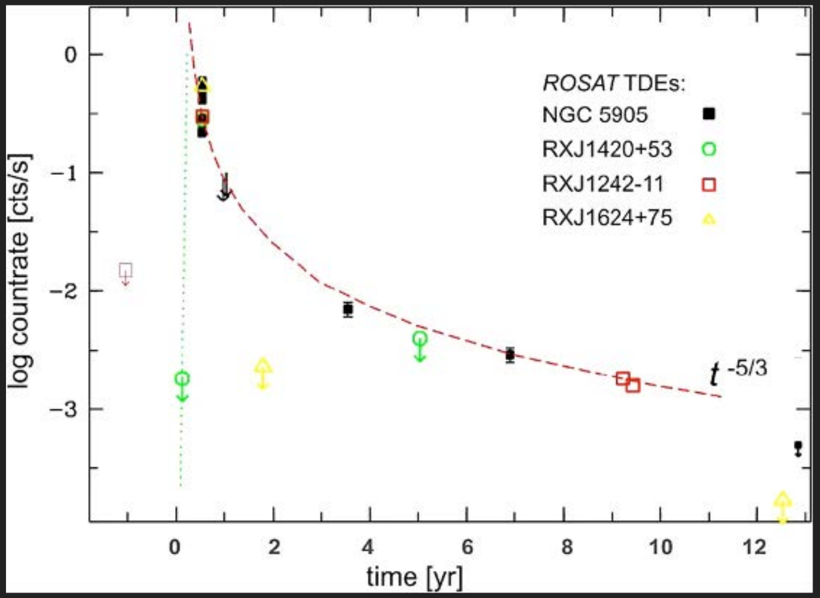
hydrodynamic-model + radiation transfer (+ nuclear reactions…)

(M_{BH}, a_{BH}, r_p, e, i, M_*, age, composition…)

↓

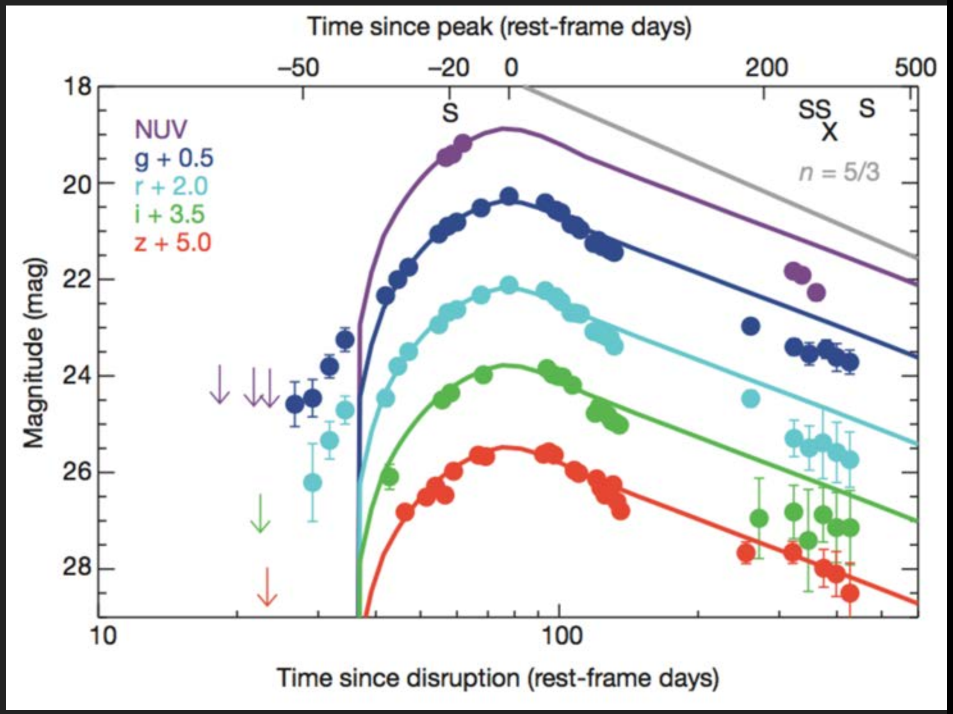
light curves + spectra

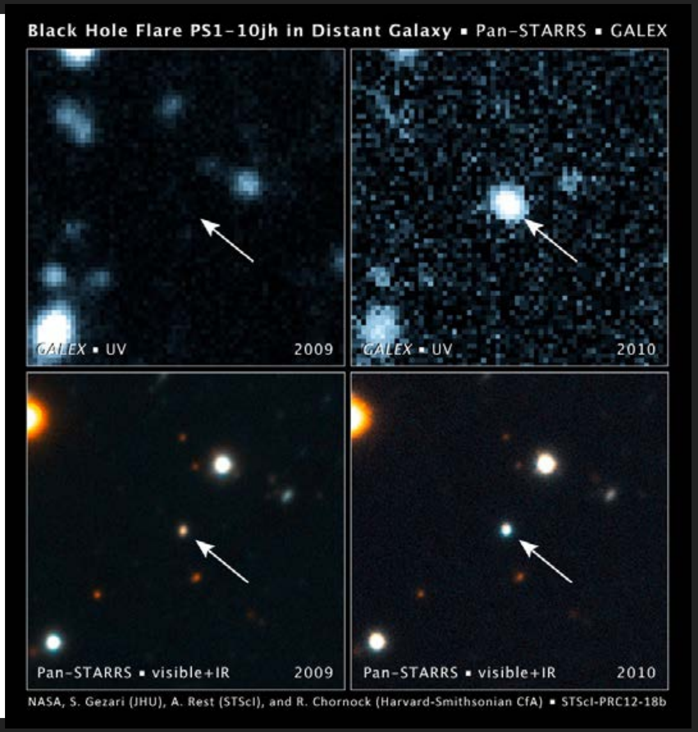
Komossa 2004



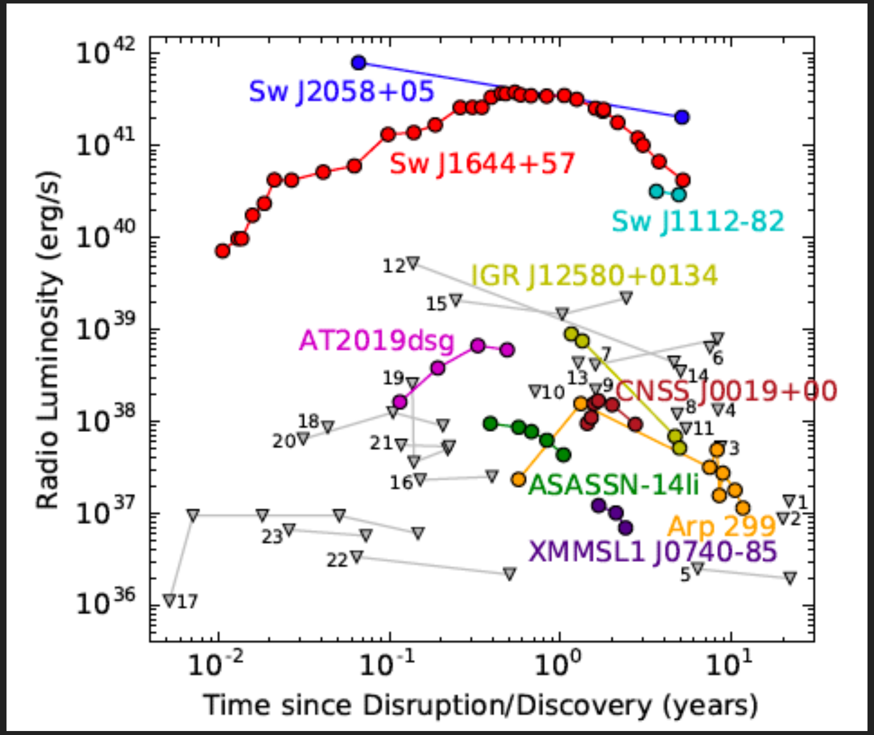
OBSERVATIONS

- X-ray flares - ROSAT all-sky survey in 1990s
- UV/optical
- radio
- jets





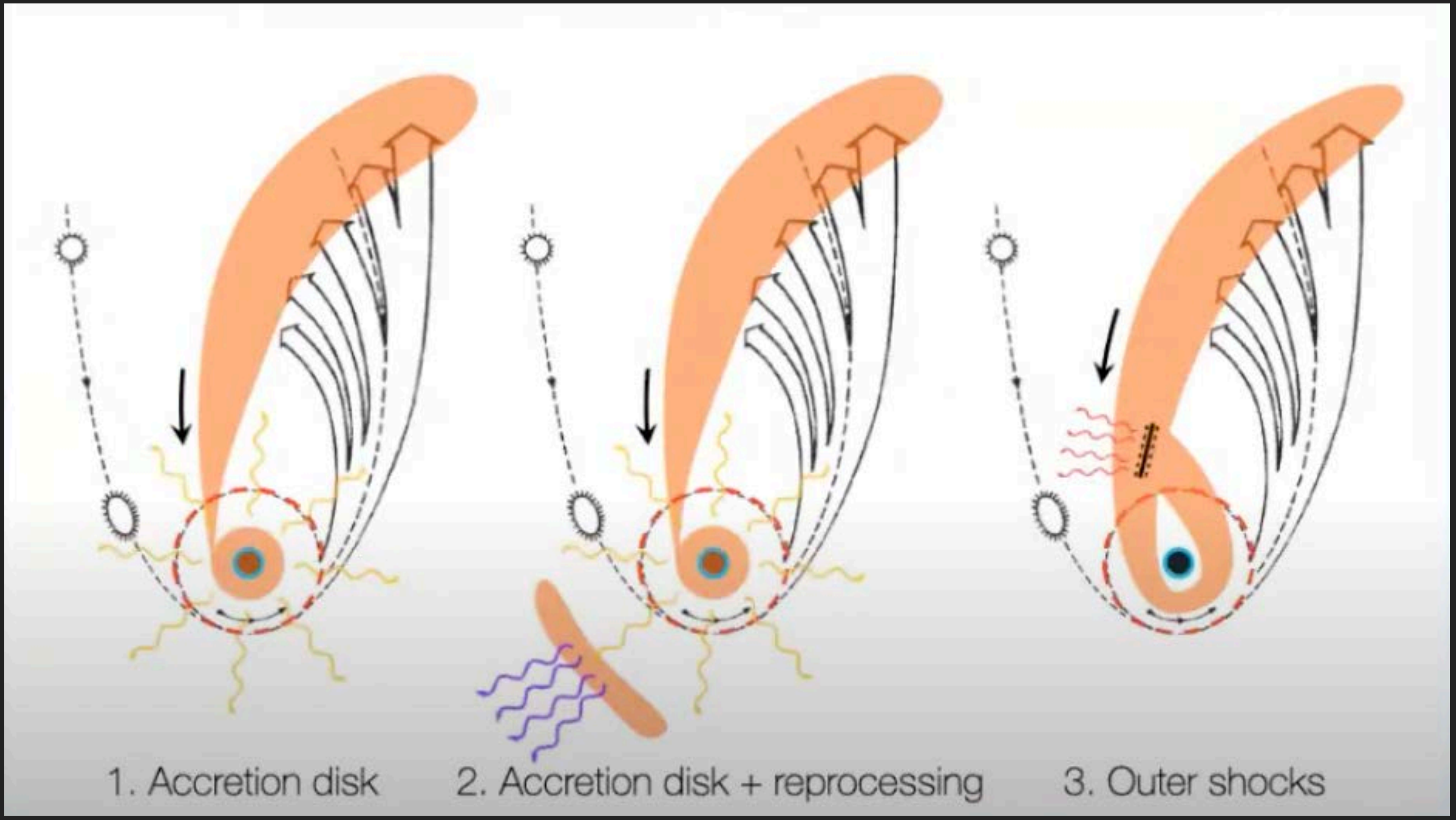
Gezari et al. 2012



Alexander et al. 2020

ORIGIN OF THE EMISSION?

- X-ray - disk
- UV/optical?
- reprocessing envelope
- shocks
- outflow



Bonnerot

- 12 UV/optical & X-ray TDEs show variability in X-rays and a smooth power-law in UV/optical
- some TDEs are bright in UV/optical and not in X-rays (and vice versa)
- some are bright in UV/optical and in X-rays

OBSERVATIONS

- nuclear transients, rate ~ 100 $\mathrm{Gpc^{-3}\ yr^{-1}}$,

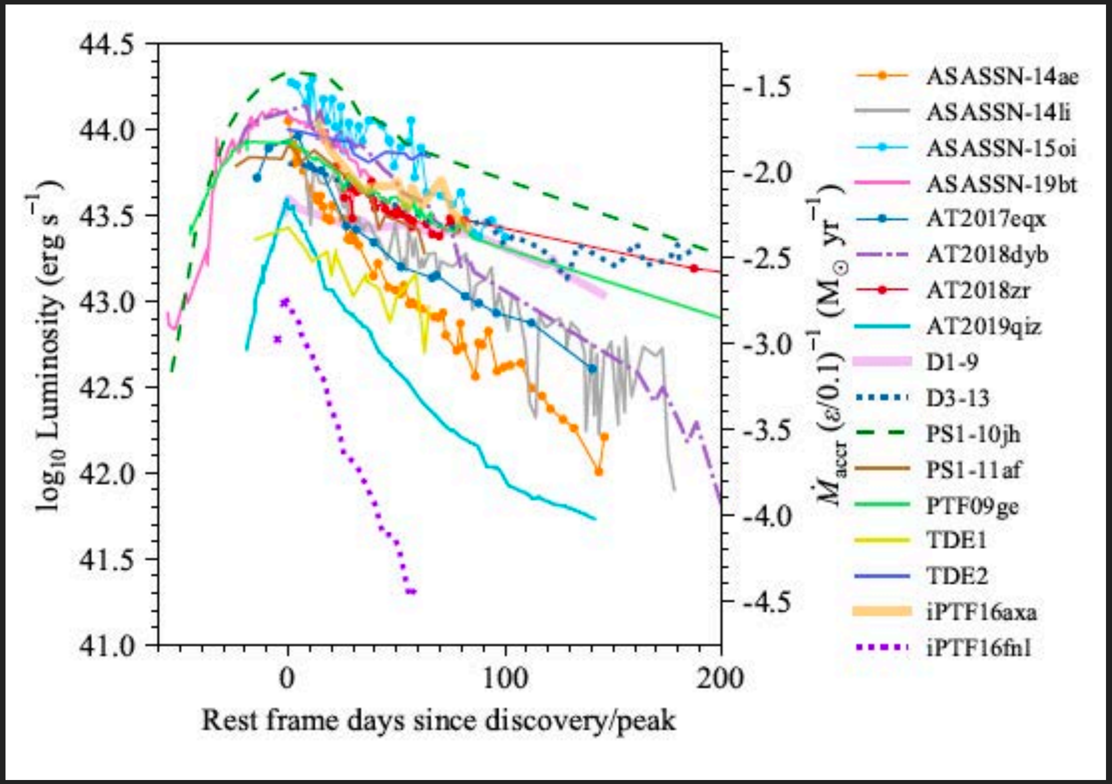
  10^{-4} $\mathrm{galaxy^{-1}\ yr^{-1}}$

- about 90 TDE candidates, 33 robust (review: van Velzen et al. 2020) - see talk by Rupak Roy

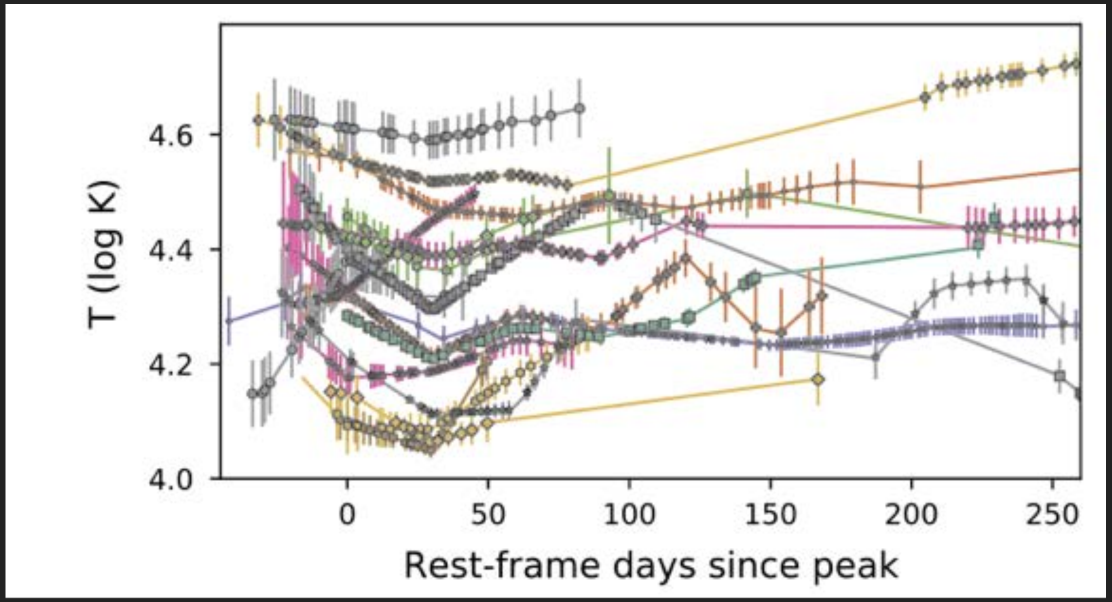
- rise ~month, decay $t^{-5/3}$, UV/opt peak ~ -20 mag

- high black body temperatures (T ~2.10^4 K, persists): blue colors

constant blue colors for months after peak are typical for TDEs



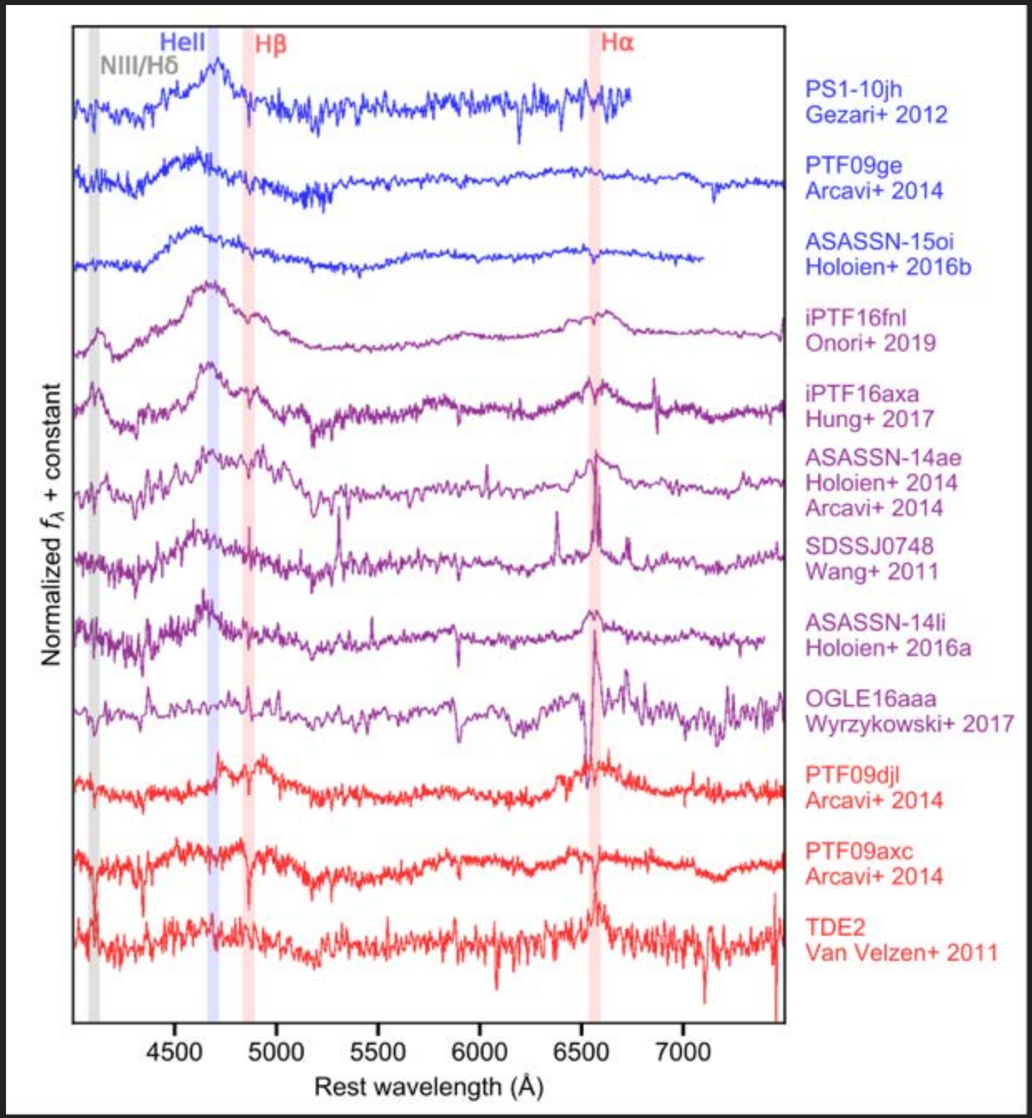
van Velzen et al., 2020



OPTICAL SPECTRA

- broad emission lines superimposed on a strong and consistent blue continuum
- He II λ4684 and/or Hα, Hβ emission lines
- TDE-H, TDE-He, TDE-H+He classes
- majority of H+He TDEs show Bowen fluorescence lines
- N III, O III, N II…
- diversity between spectral types associated with the radius and temperature of the photosphere

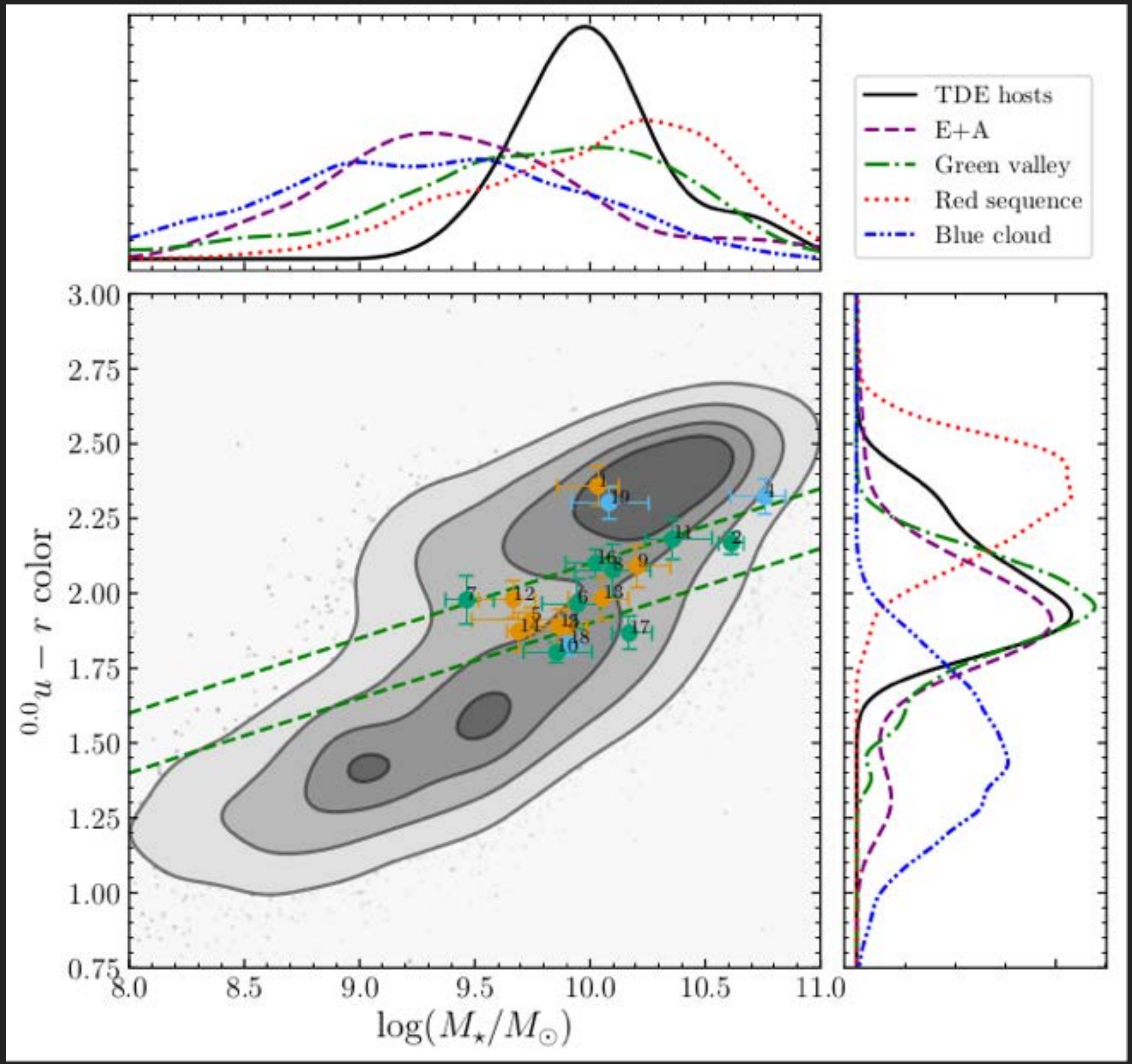
spectra are very important for classification.



van Velzen et al., 2020

HOST GALAXIES

- preference for Quiescent Balmer Strong (QBS) galaxies and their subset of post-starburst E+A galaxies
- rare in the local Universe (~2%), but over-represented among TDE hosts
- low star formation rates with a recent star formation burst, which ended in the last ~Gyr
- located in the green-valley with large concentration of stars near the center
- TDEs occur in other galaxies as well

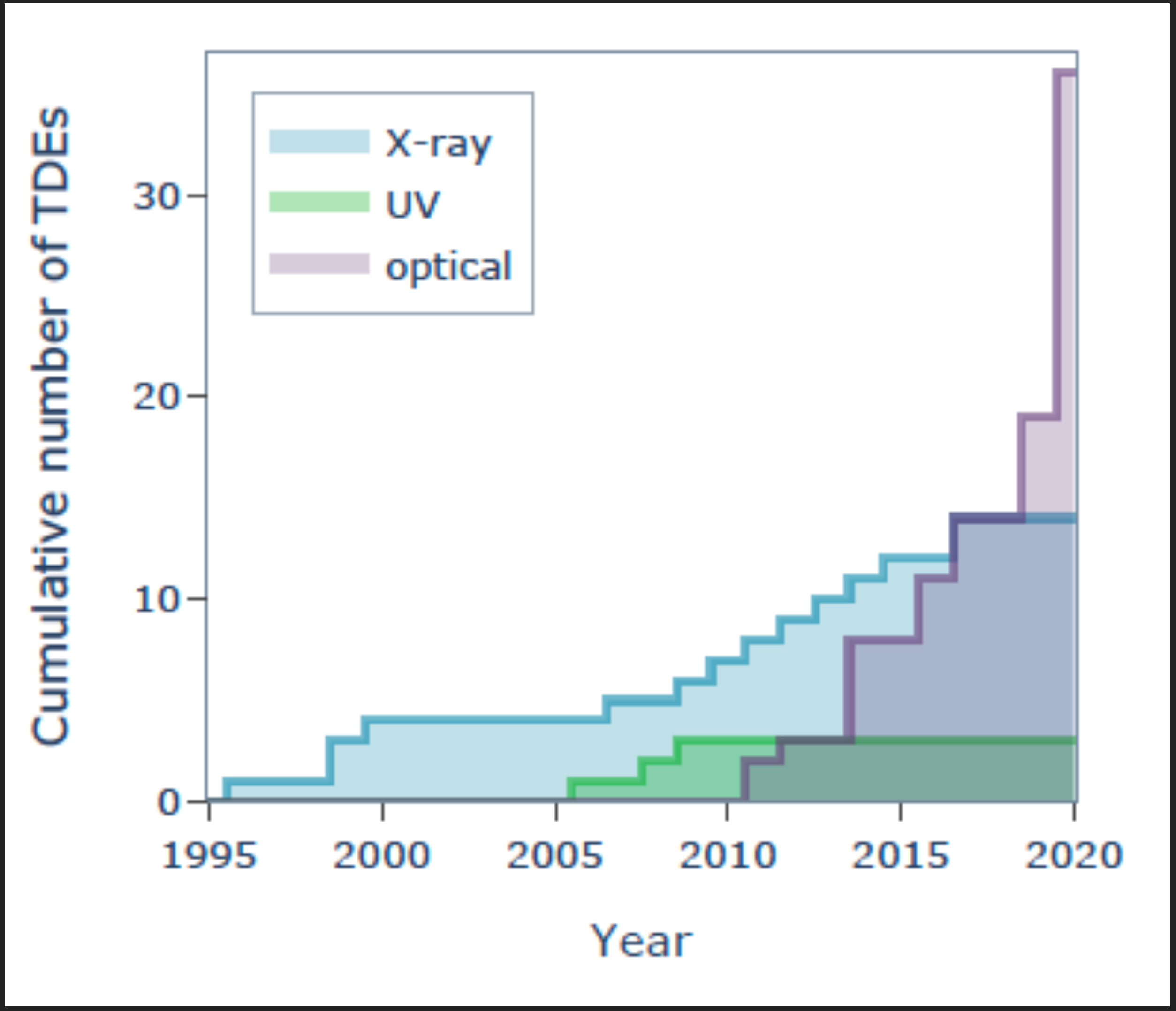


Hammerstein et al 2021

PROBES

- SMBHs in non-active galaxies
- stellar population and dynamics
- accretion efficiency
- TDE rates with z, host galaxy type
- etc.

current discovery rate ~ 10/yr

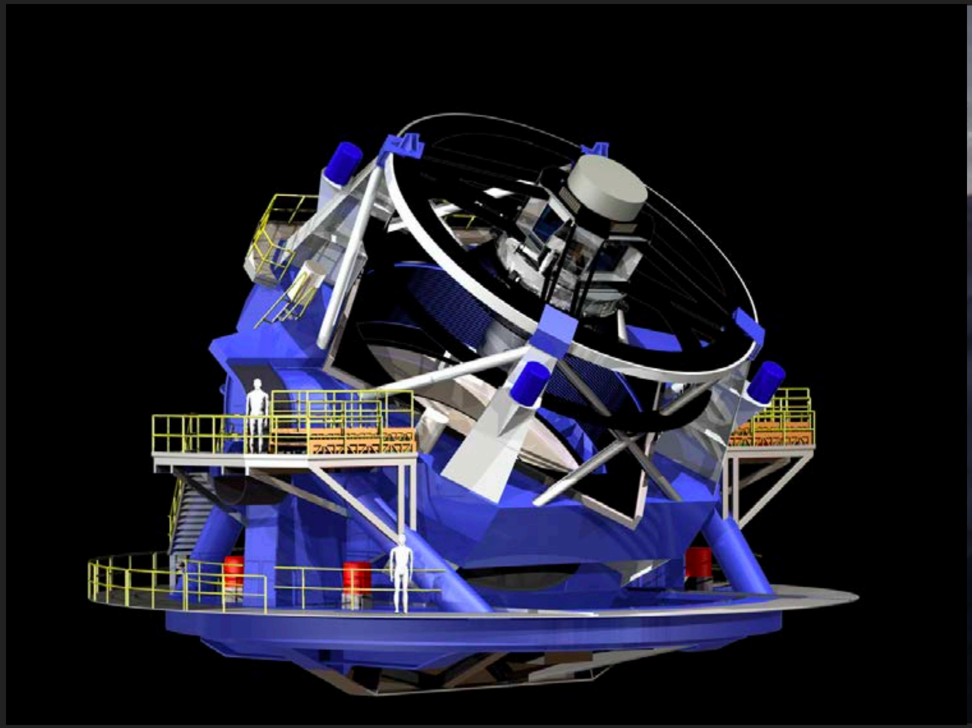


Gezari 2021, Bučar Bricman 2021

VERA C. RUBIN OBSERVATORY LEGACY SURVEY OF SPACE AND TIME - RUBIN LSST

Cerro Pachon, Chile,
8,4-m telescope
10-year survey
u, g, r, i, z, y
limiting magnitude r~24.5 in a single exposure
r~27.5 coadded

Vera Rubin
(1928-2016)



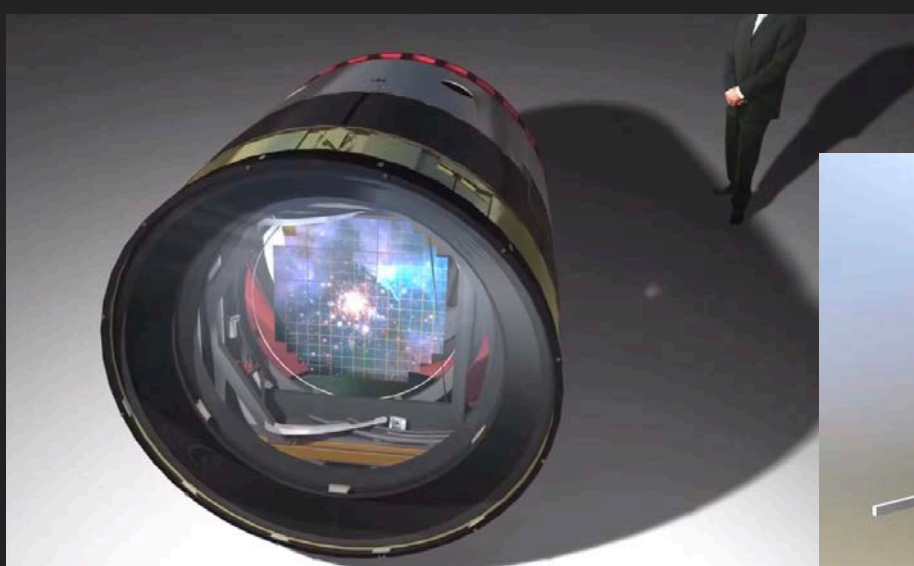
Simonyi Survey Telescope

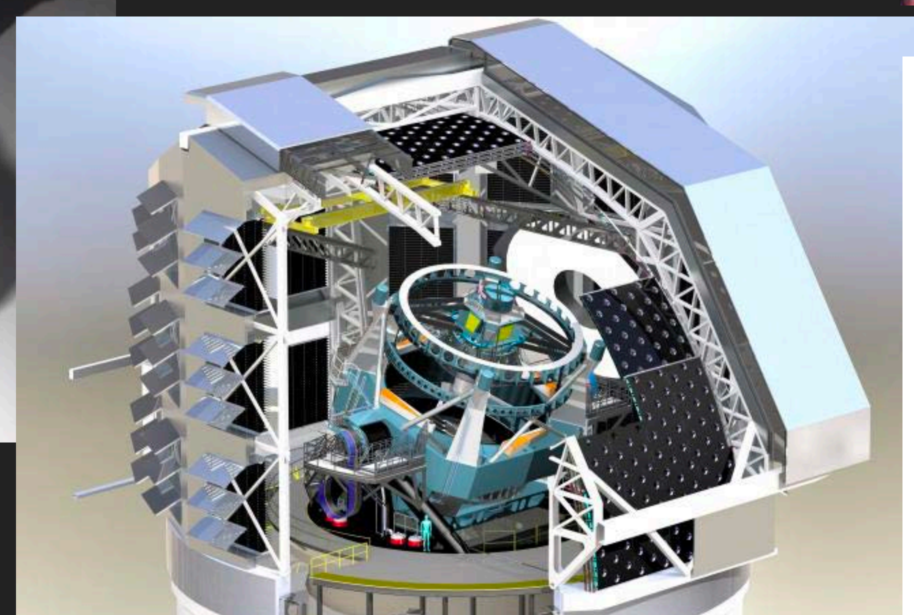
WIDE-FAST-DEEP

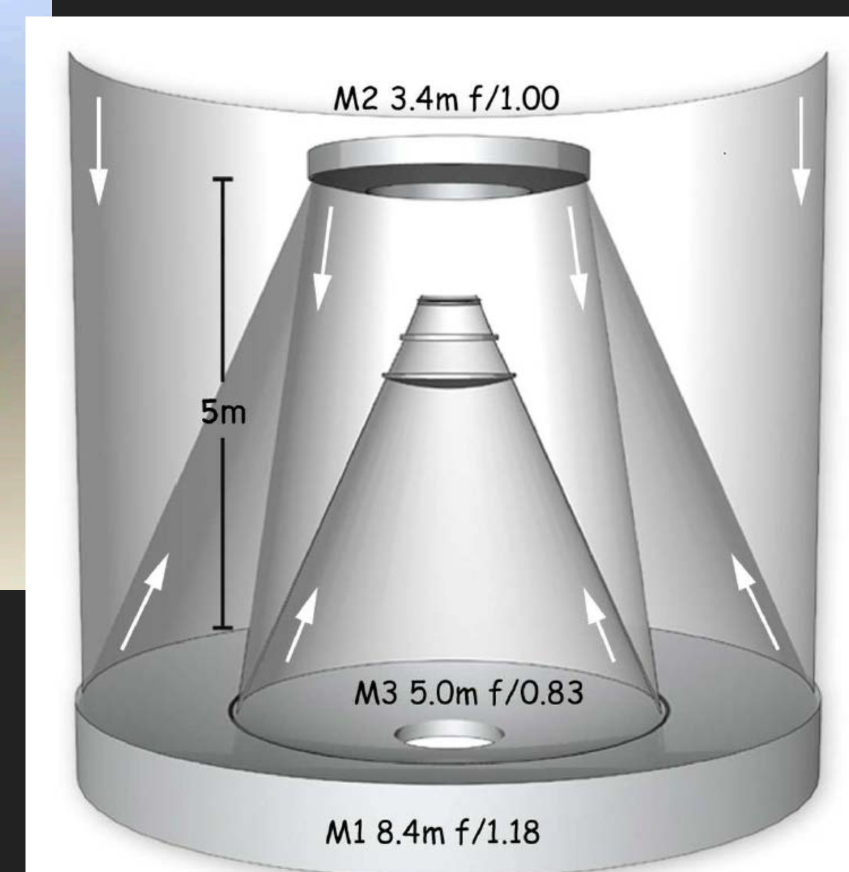
FoV 9.6 deg^2 - to cover large areas of sky to faint magnitudes in a short amount of time

10.000 deg^2 /night

3.2 Gigapixels camera







1000 frames/night

about 30-40 TB data/night

in total 500 PB data and data products

FOUR MAIN SCIENCE GOALS

An inventory of the Solar System including Near Earth Asteroids and Potential Hazardous Objects, Main Belt Asteroids, and Kuiper Belt Objects

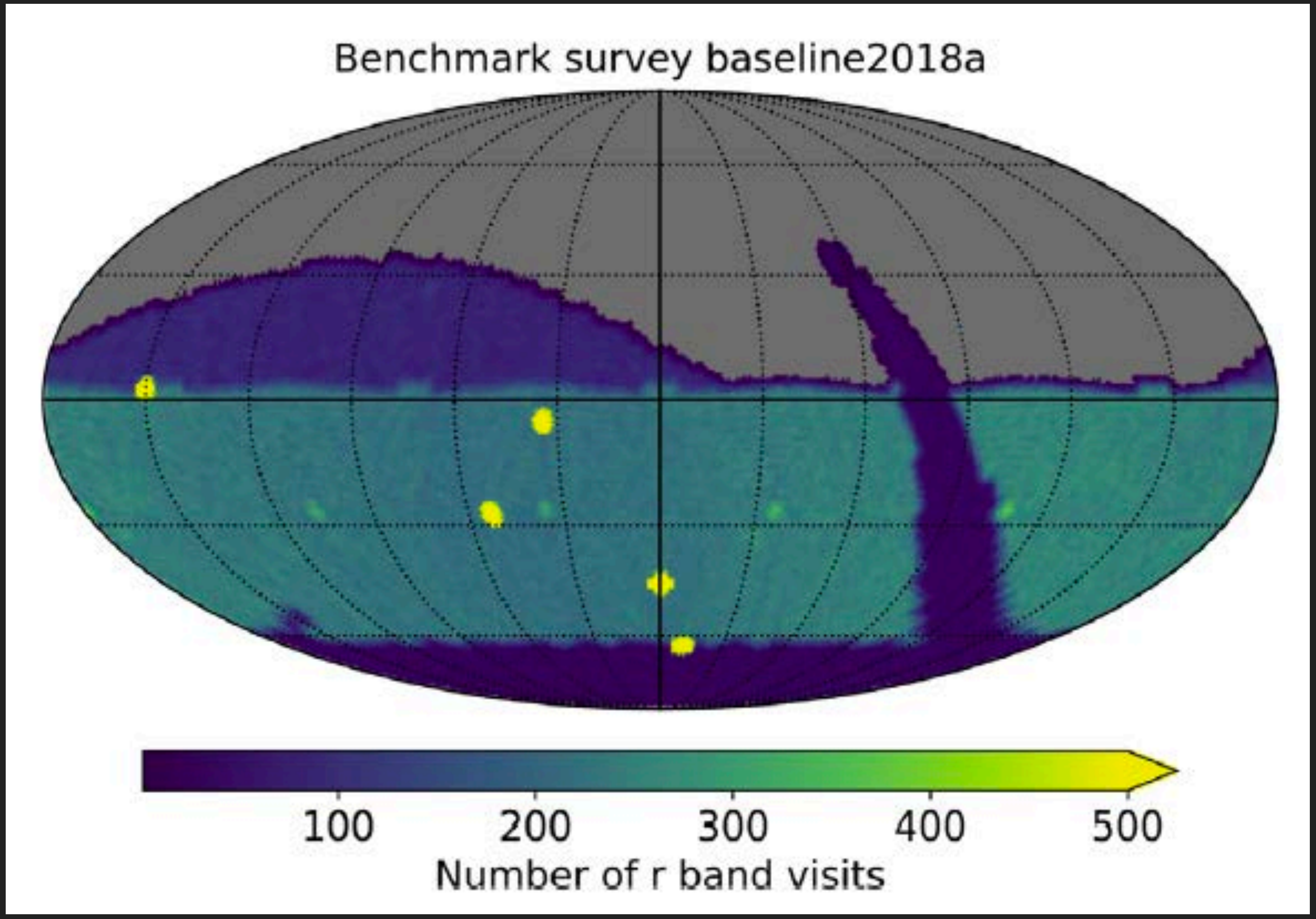
Studying the structure of the Milky Way galaxy and its neighbors via resolved stellar populations

Constraining dark energy and dark matter (via measurements of strong and weak lensing, large-scale structure, clusters of galaxies, and supernovae)

Exploring the transient and variable universe

BASELINE OBSERVING STRATEGY

- main "Wide-Fast-Deep" (WFD) survey
- 5 Deep Drilling Field candidate mini surveys
- Galactic Plane candidate mini survey
- North Ecliptic Spur candidate mini survey
- South Celestial Pole candidate mini survey



The LSST Baseline Design and Survey Parameters

Quantity	Baseline Design Specification
Optical config.	Three-mirror modified Paul-Baker
Mount config.	Alt-azimuth
Final f-ratio, aperture	$f/1.234$, 8.4 m
Field of view, étendue	9.6 deg^2, 319 m^{2}deg^2
Plate scale	50.9 μm/arcsec (0.″2 pix)
Pixel count	3.2 gigapixels
Wavelength coverage	320–1050 nm, *ugrizy*
Single-visit depths, design[a]	23.9, 25.0, 24.7, 24.0, 23.3, 22.1
Single-visit depths, min.[b]	23.4, 24.6, 24.3, 23.6, 22.9, 21.7
Mean number of visits[c]	56, 80, 184, 184, 160, 160
Final (co-added) depths[d]	26.1, 27.4, 27.5, 26.8, 26.1, 24.9

Ivezić et al 2019

~ 825 visits/field

DATA…

A catalog of 37 billion objects: 20 billion galaxies, 17 billion stars

A catalog of orbits for 6 million bodies in the Solar System.

A stream of 1-10 million time-domain events per night, detected and transmitted within 60 s of observation: moving objects, variable stars, explosions…:

- ~ 10 -135 million variable stars (in the beginning ~100.000/night, 7000/visit)
- ~ 3000 AGNs/night (in total millions of AGNs)
- ~ 1100 SNe/night (380 SN Ia/night)

….

- TDEs - ?

SNe discovered over 30 years

PROSPECTS OF OBSERVING TDES WITH THE LSST?

- LSST Software Stack - to evaluate LSST performance
- Operations Simulator (cadence, site conditions, HW and SW…) - used minion_1016 cadence
- added TDEs in Catalog Simulator - using MOSFiT (Guillochon et al. 2018) to calculate SED
- 1 M_S, parabolic orbit
- varied impact parameter and BH mass

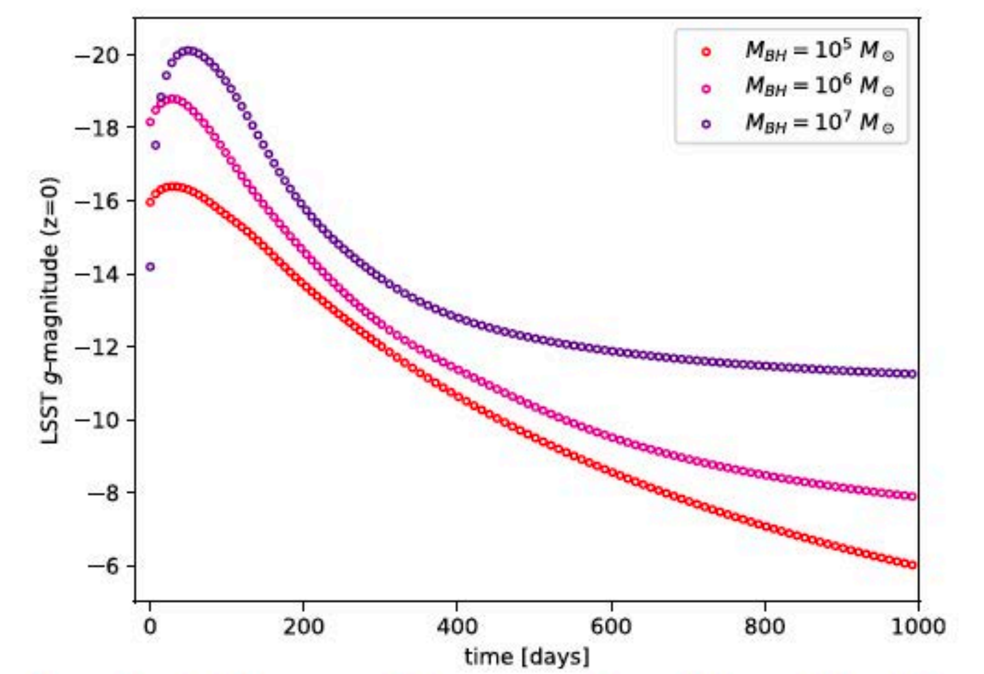
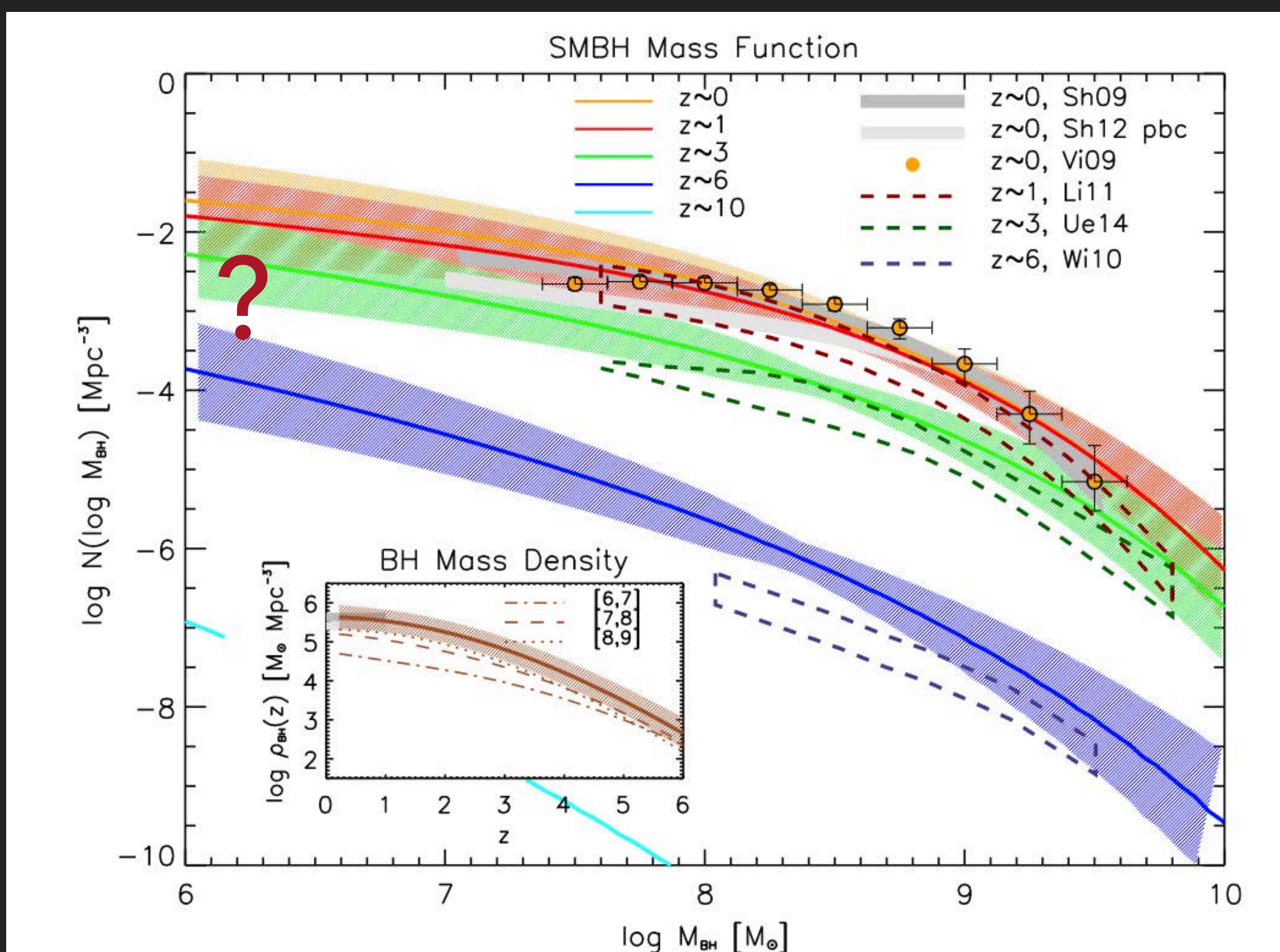


Figure 1. MOSFiT-generated light curves of three TDEs with black hole masses: $10^5\ M_\odot$ (red), $10^6\ M_\odot$ (pink), and $10^7\ M_\odot$ (violet). In all three events a solar-type star disruption with $\beta = 1$ was assumed. The absolute magnitudes were calculated in the LSST g band.

Bricman & AG, 2020

SMBH MASS DISTRIBUTIONS

- uncertainties in distribution over BH mass at low mass end



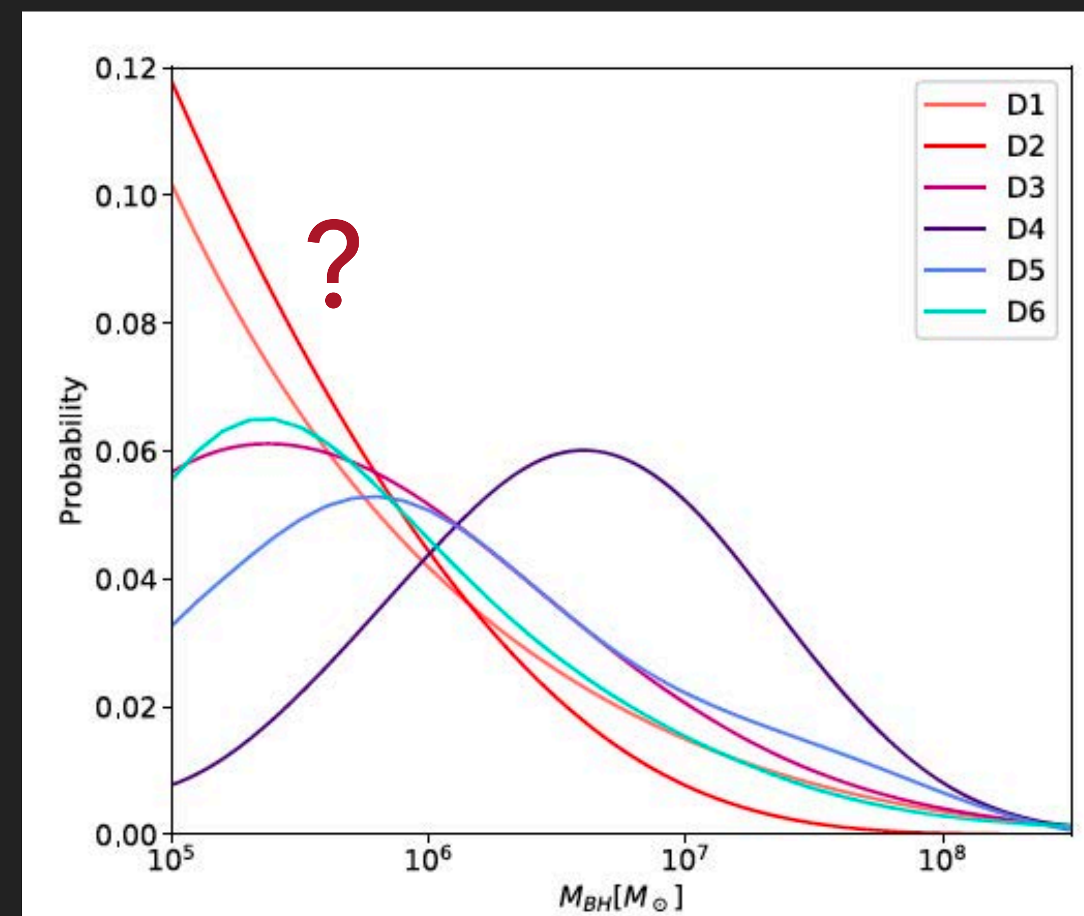


Figure 2. Input SMBH mass probability distributions D1–D6.

Aversa et al 2015

DIFFERENT REDSHIFTS & 20 FIELDS IN THE SKY:

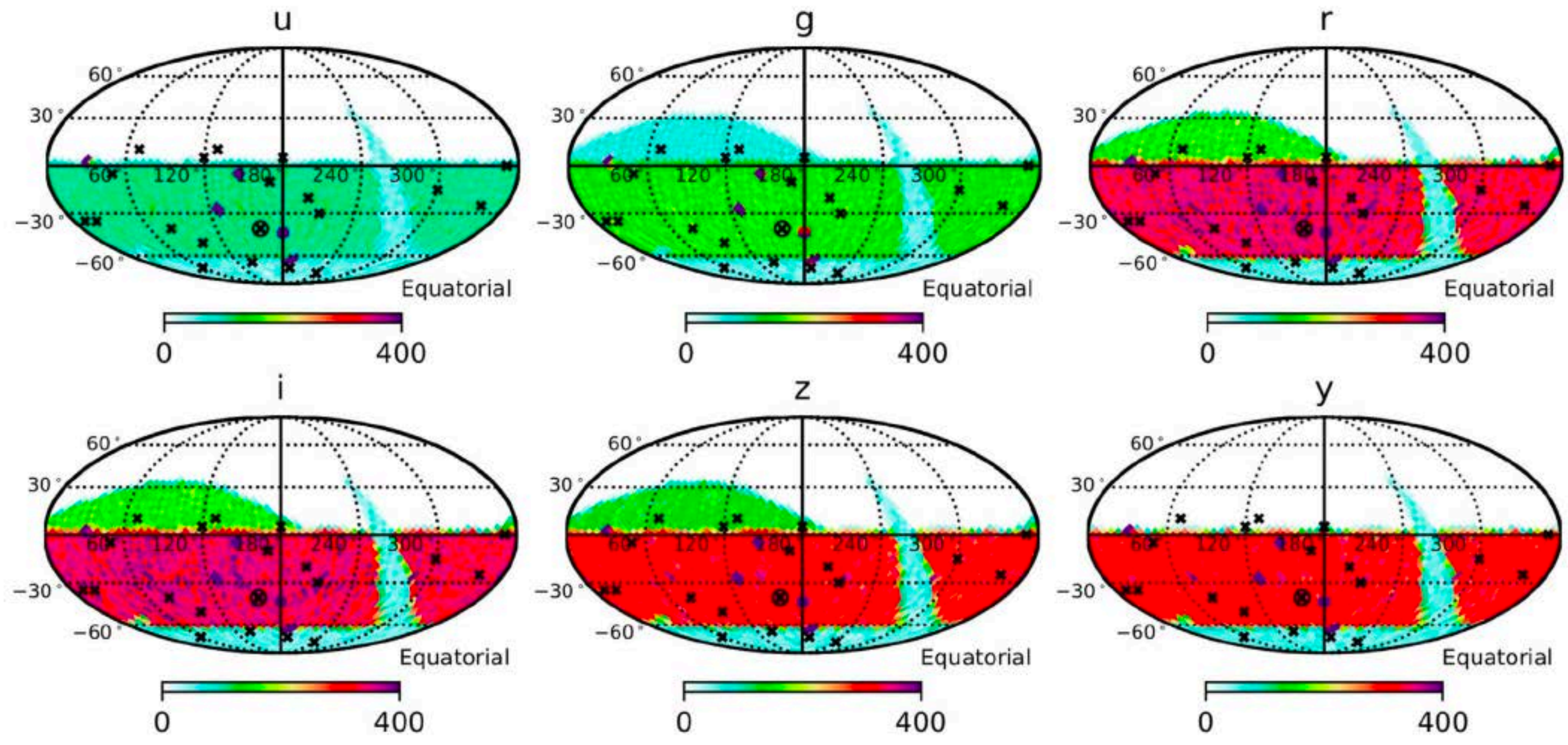
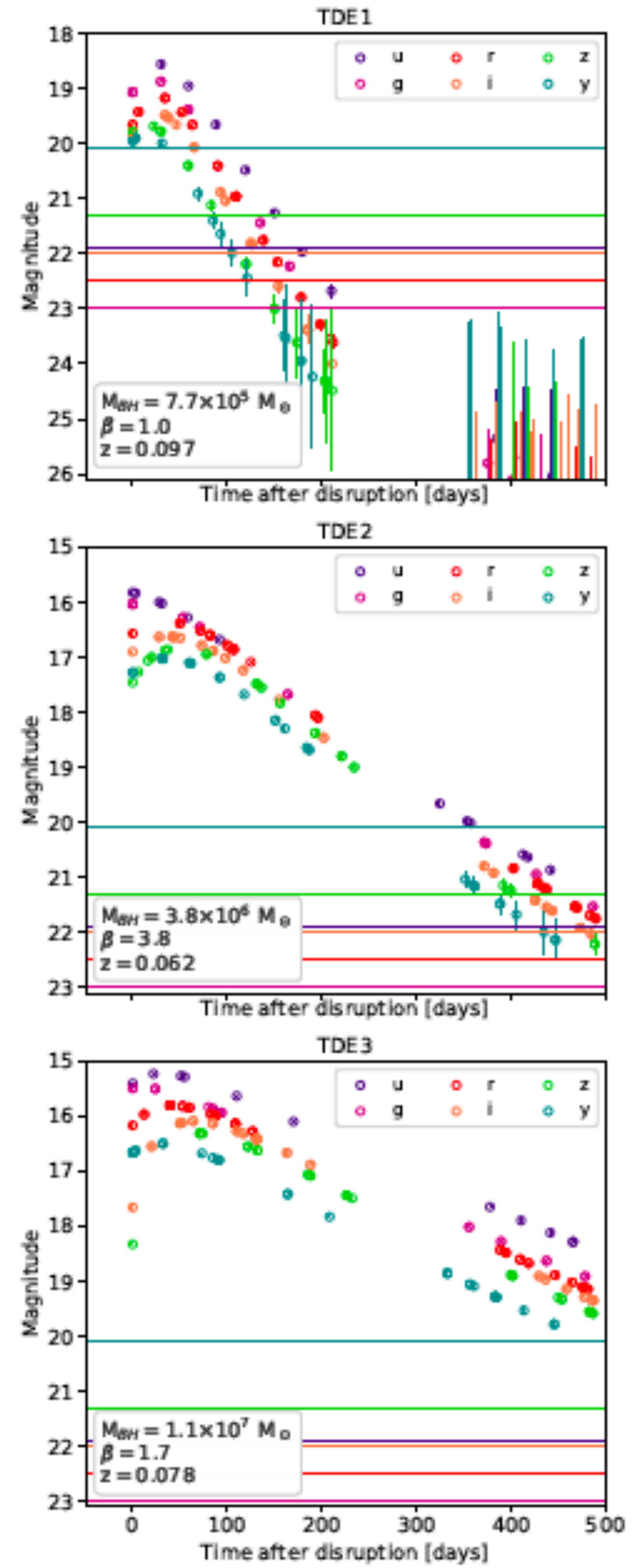


Figure 3. Number of visits (where a visit consists of two 15 s exposures) to a given field on the sky over 10 years of LSST observations in all six bands (*u*, *g*, *r*, *i*, *z*, and *y*) according to the observing strategy `minion_1016`. Observations in the *r*, *i*, *z*, and *y* bands will be more common than those in the *u* or *g* band, which is also apparent from the panels corresponding to each of the bands. The distribution of number of visits on the sky is irregular, as the cadence proposed is also irregular. Black crosses mark the locations of fields on which we simulated TDEs.

WHAT COUNTS AS A DETECTION?

10 observations above cutoff magnitude:

u_c=21.5, g_c=22.8, r_c=22.4, i_c=21.9, z_c=21.3, y_c=20.1



NUMBER OF TDES DETECTED

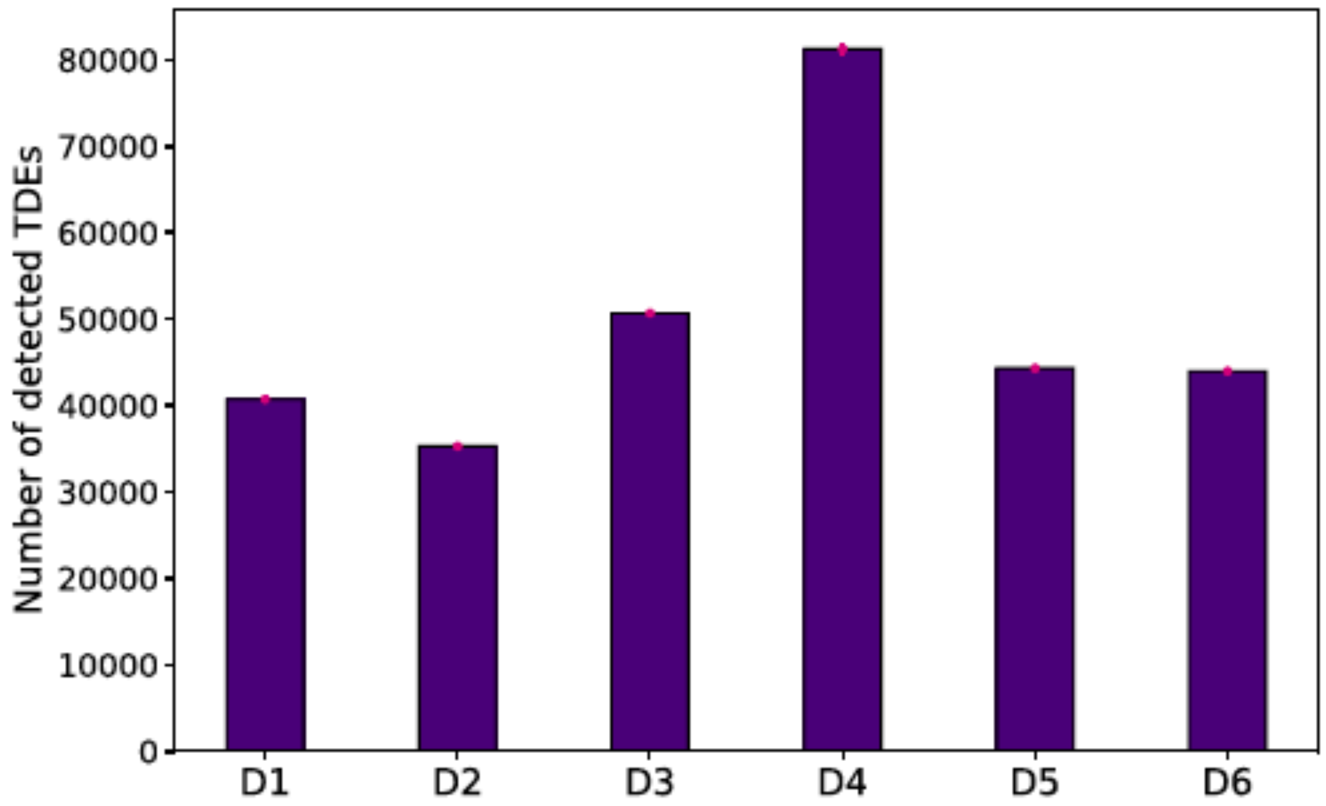


Figure 6. Number of detected TDEs for each of the SMBH mass distributions D1–D6. The number of expected detections is between 35,000 ± 260 and 80,000 ± 400 over 10 years of observations. This corresponds to average values between 10 and 22 TDEs per night.

rate of TDEs: 10^{-5} galaxy^{-1} yr^{-1}

~10 - 22 TDEs/night

identification?

follow-up observations?

PROBING THE SMBH MASS DISTRIBUTION

low mass BHs produce fainter and shorter TDEs

not straightforward :-(

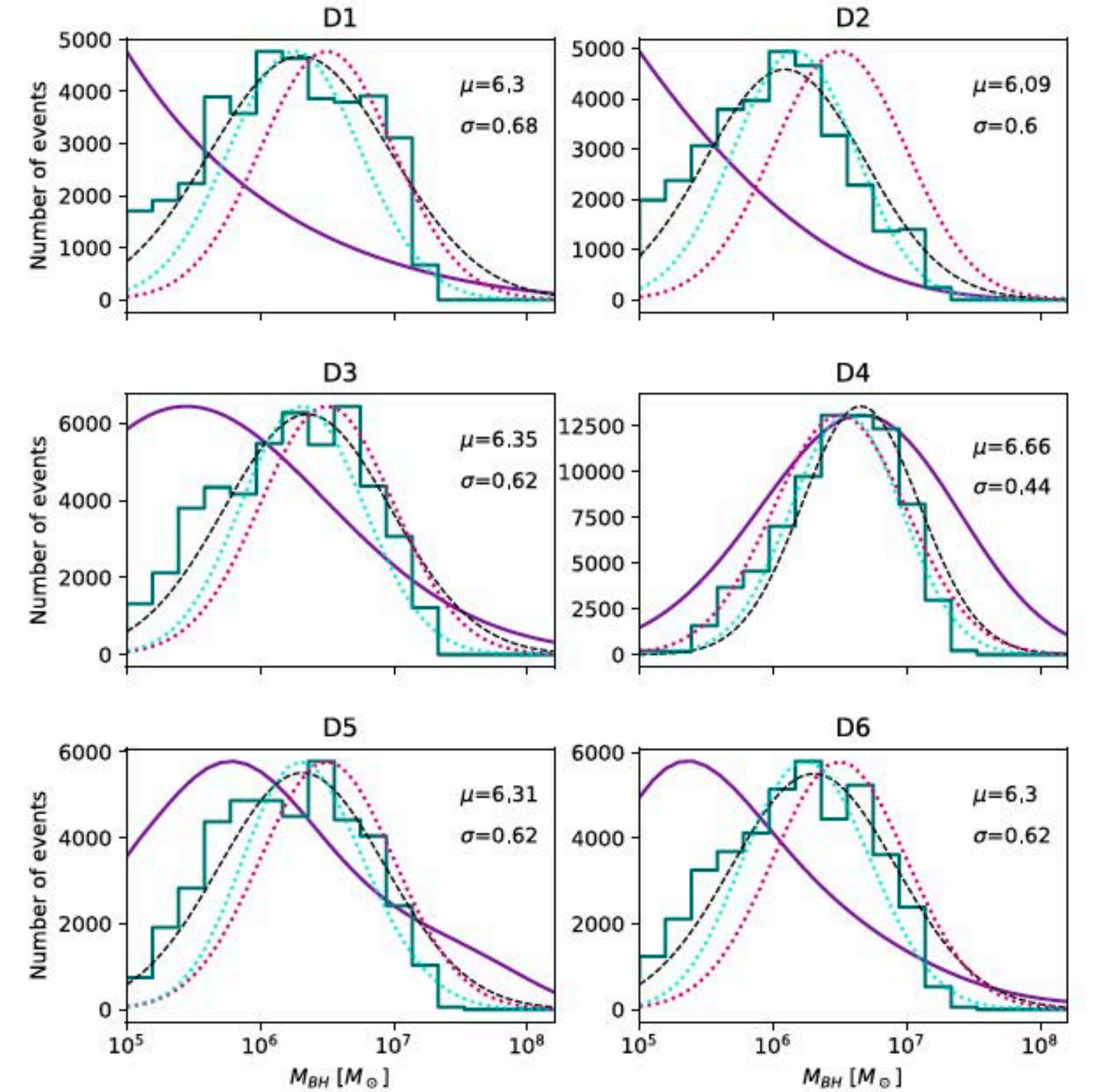


Figure 7. Input theoretical SMBH mass distributions D1–D6 (purple lines), the SMBH mass distribution of detected TDEs (green histograms), the Gaussian fit to detected TDEs (black dashed line), and the selection-effects function (pink dotted line). The observed samples consist of all detected TDEs on 20 simulated fields, scaled to the whole observable sky as discussed in 5.2.

OTHER STRATEGIES PROPOSED

- > 200

7 main survey parameters:

- Survey footprint modifications: WFD area from 18, 000 deg^2 to 20, 000 deg^2.
- Exposure time per visit: u-band visit - 1x 50 s exposure, retaining the same overall number of visits in u-band
- Allocation of observing time per band: changes in the filter distributions across visits
- Cadence and revisit times variations : visits in a pair in the same or in mixed filter, or adding an additional visit
- Rolling cadence: sky is split into a defined number of declination bands, receiving a higher number of visits during an “on” season followed by a lower number of visits during an “off” season.
- The footprint of mini-surveys : footprints of GP, North Ecliptic Spur, and South Ecliptic Pole mini surveys, DDFs footprint, location and cadence.
- Twilight observations: changing the cadence and filter distribution during twilight observations

EFFECTS ON TDE OBSERVATIONS?

- TDE metric - with Katja Bučar Bricman, Sjoert van Velzen, Federica Bianco in LSST TVS SC
- TDE impostors: SN Ia, AGNs… photometric identification required
- important to resolve the peak and colour - TDE are (and remain) blue

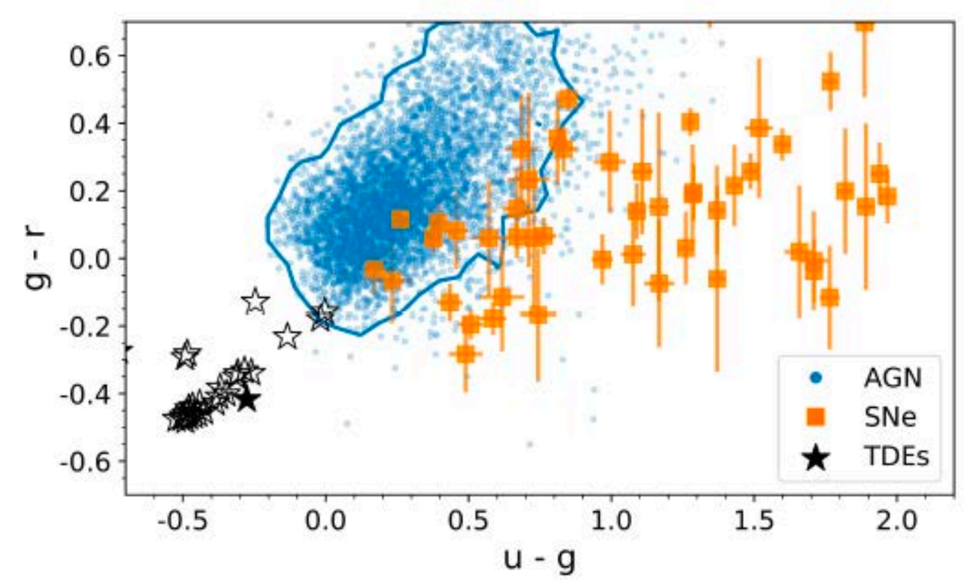


Figure 1: Color-color diagram of nuclear transients: mean $g-r$ color against mean $u-g$ color of the decaying phase of the light curve. TDEs lie in the lower left part of the diagram, with blue mean colors $u-g \sim -0.5$ and $g-r \sim -0.4$, making them clearly recognizable from SNe and AGN. Plot is adapted from van Velzen et al. (2011) and has been updated with recently observed TDEs.

van Velzen 2020

TDESPOP METRIC

- input: PS1-10jh, iPTF-16fnl @z=0.05, 0.1, 0.2
- rate: 3/night
- ObsSim

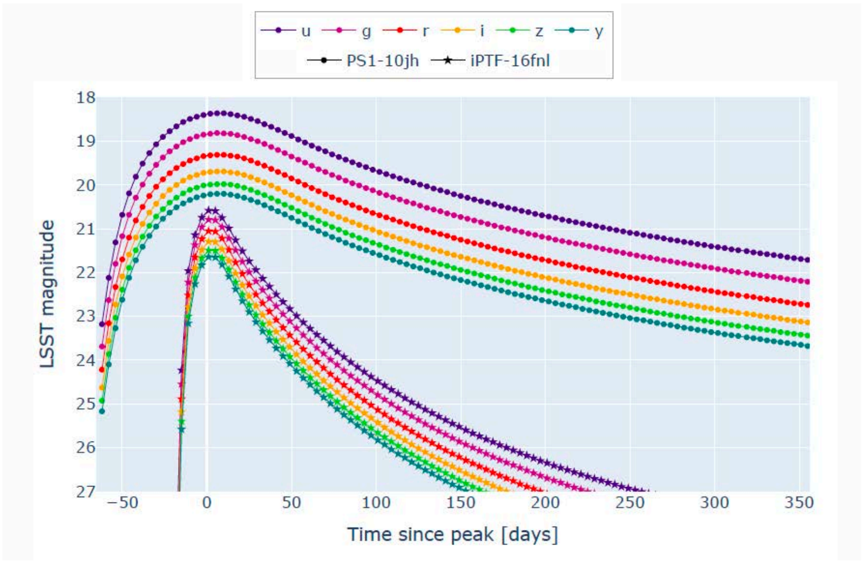
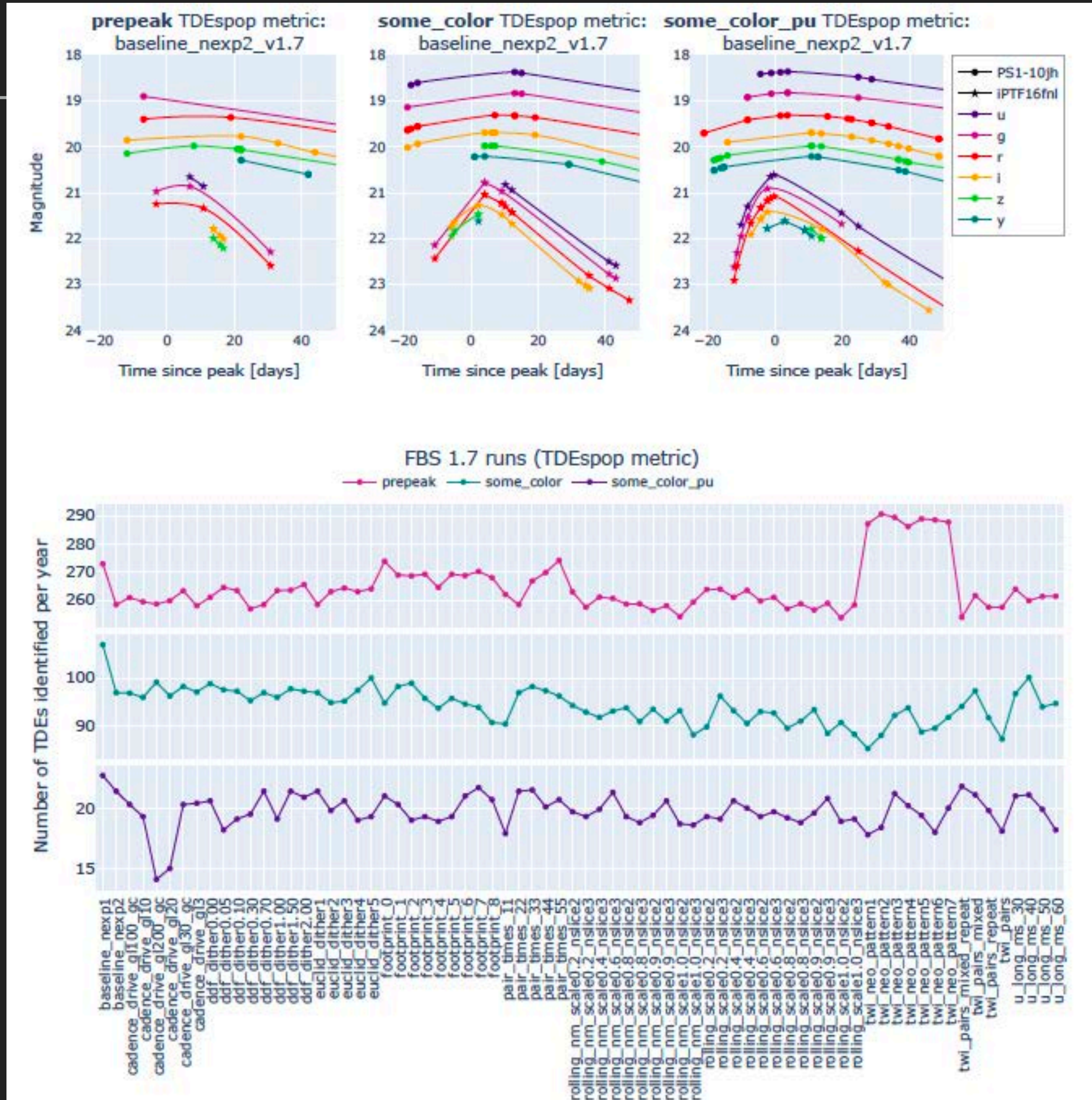


Figure 2: Sample TDE light curves for TDEs_pop metric. Rubin magnitudes are plotted for PS1-10jh (bullet symbols) and iPTF16fnl (star symbols), both calculated at redshift of $z = 0.1$.

TDEspop metric 3 sets of criteria (minimum):

- prepeak: 2 detections before the peak
- some_color: 1 detection pre-peak, 3 filters within 10 d of the peak, 2 filters 10-30 d after the peak
- some_color_pu: 1 detection pre-peak, 1 u and 1 other within 10 days of the peak, 1 u and 1 other in 10-30 d after the peak



N_{input}=1000

25%

10%

2%

TDE FILTERING PLANS

- real-time image difference analysis (in 60 s) → LSST Alerts Stream
- brokers: Alerce, AMPEL, ANTARES, BABAMUL, FINK, Lasair, Pitt-Google
- filtering - information included in the LSST Alerts: history, photometric light curve, astrometric data/galaxy cross match, offset from gc, photo-z, galaxy colour/type
- challenge: how to reliably identify a TDE based solely on LSST photometry? before the peak? - to enable follow-up
- TDE filtering based on: nuclear position, light curve features, colour (evolution), absolute peak magnitude (photo-z), galaxy type, machine learning…
- in development…

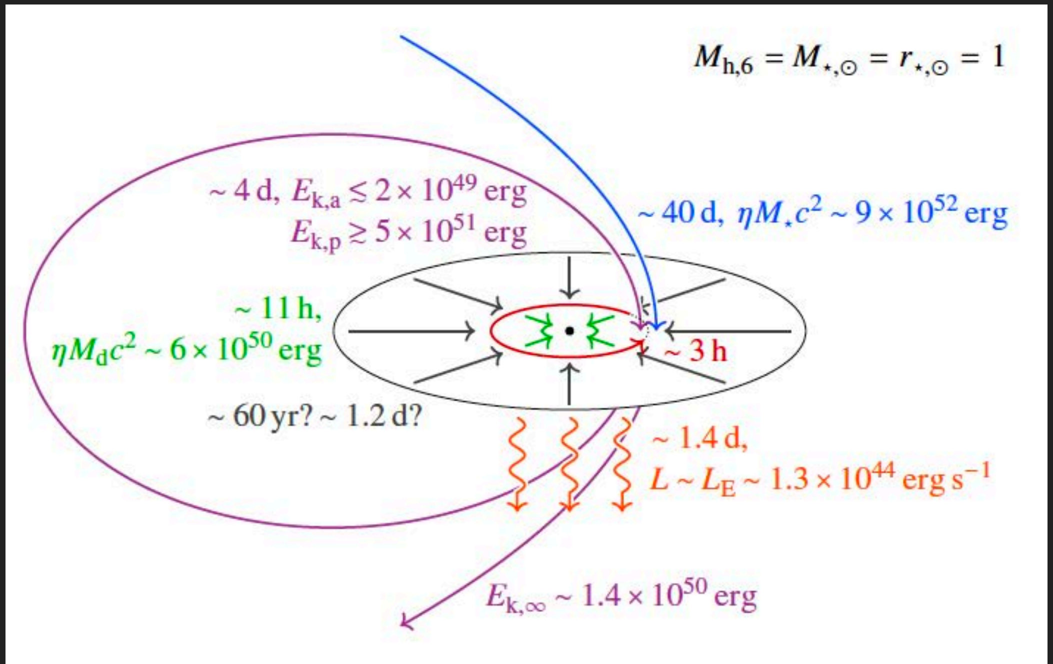
TAKE AWAY MESSAGES

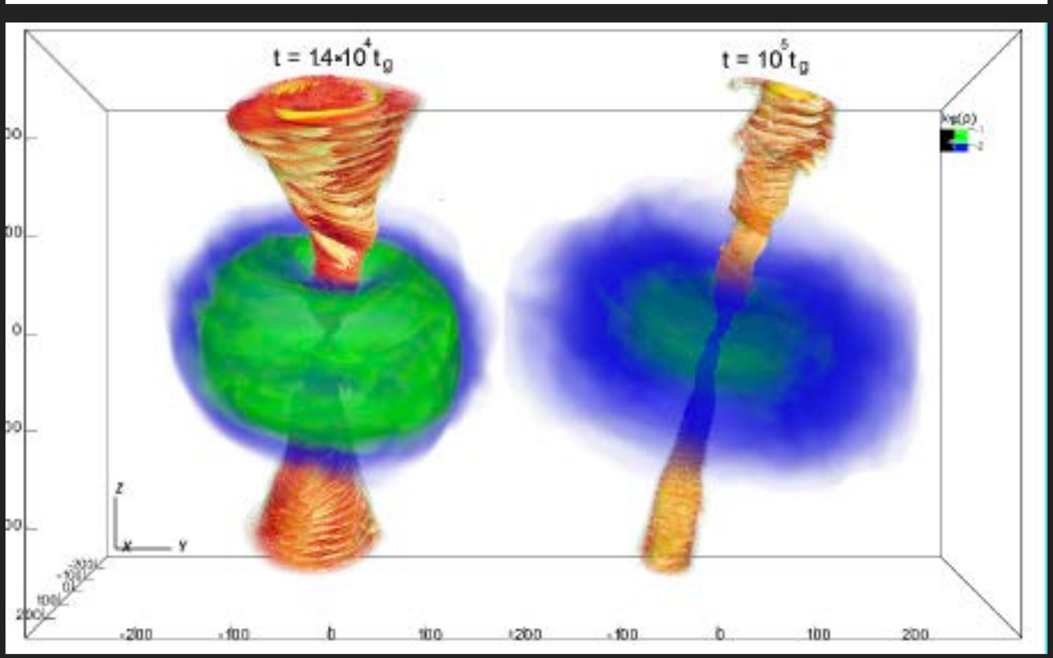
- ~10-100 TDEs/night detected with Rubin LSST
- challenge: identification of TDEs! - looking for a postdoc
- help or bias? - blue colour, nuclear, non-AGN, type of galaxy…
- population/statistical studies

OTHER INTERESTING TDE TOPICS….

- non-nuclear TDEs
- TDEs in AGNs
- TDEs with jets
- TDEs as multi-messenger sources
- testing GR with TDEs
- …

Chan et al. 2020





Roth et al. 2016